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Evaluation of dynamical track predictions for tropical cyclones in the Atlantic during 1997-98

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THESIS

EVALUATION OF DYNAMICAL TRACK PREDICTIONS FOR TROPICAL CYCLONES IN THE ATLANTIC DURING 1997-98

by

David S. Brown

March 2000

Co-Thesis Advisors: Russell L. Elsberry
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Carr and Elsberry (1999; NPS Tech Report) have described eight conceptual models that explain most cases of large (> 300 n mi at 72 h) western North Pacific tropical cyclone (TC) track errors by the Navy Operational Global Atmospheric Prediction System (NOGAPS) and the Geophysical Fluid Dynamics Lab (Navy version - GFDN) models. This study is for TCs in the Atlantic basin and includes the European Centre for Medium-range Weather Forecasting (ECMWF) and the United Kingdom Meteorological Office global models, whereas the GFDL model is eliminated. A detailed examination is made of large (> 250 n mi at 72 h) errors made by the three dynamical models for two seasons of Atlantic TC tracks (1997-98). The percentages of > 250 n mi 72-h errors for the NOGAPS, UKMO, and ECMWF models were 23%, 26%, and 19%, respectively. The same error mechanisms found to apply in other basins also affect the dynamical models in the Atlantic. The NOGAPS and UKMO models have a tendency to over-represent TCs and other circulations, which leads to a cyclonic rotation, or even merger, via the Excessive Direct Cyclone Interaction (E-DCI) process, just as was found in the western North Pacific. The primary ECMWF error source was Excessive Midlatitude CycloGenesis (MCG).

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EVALUATION OF DYNAMICAL TRACK PREDICTIONS FOR TROPICAL CYCLONES IN THE ATLANTIC DURING 1997-98

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requirements for the degree of

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ABSTRACT

Carr and Elsberry (1999; NPS Tech Report) have described eight conceptual models that explain most cases of large (> 300 n mi at 72 h) western North Pacific tropical cyclone (TC) track errors by the Navy Operational Global Atmospheric Prediction System (NOGAPS) and the Geophysical Fluid Dynamics Lab (Navy version – GFDN) models. This study is for TCs in the Atlantic basin and includes the European Centre for Medium-range Weather Forecasting (ECMWF) and the United Kingdom Meteorological Office global models, whereas the GFDL model is eliminated. A detailed examination is made of large (> 250 n mi at 72 h) errors made by the three dynamical models for two seasons of Atlantic TC tracks (1997-98). The percentages of > 250 n mi 72-h errors for the NOGAPS, UKMO, and ECMWF models were 23%, 26%, and 19%, respectively. The same error mechanisms found to apply in other basins also affect the dynamical models in the Atlantic. The NOGAPS and UKMO models have a tendency to over-represent TCs and other circulations, which leads to a cyclonic rotation, or even merger, via the Excessive Direct Cyclone Interaction (E-DCI) process, just as was found in the western North Pacific. The primary ECMWF error source was Excessive Midlatitude CycloGenesis (MCG).

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I. INTRODUCTION

A. MOTIVATION

The military and civilian impacts of hurricanes along the eastern seaboard are significant. A review of the Hurricane Havens handbook for the eastern United States (Gilmore and Brand 1999) reveals the susceptibility of many of our U.S. Navy ports. For example, the recommended course of action for Norfolk is to sortie all U.S Navy ships from the Norfolk-Chesapeake Bay area and evade any threatening strong tropical cyclone at sea. Similar recommendations apply at all Atlantic and Gulf of Mexico Navy bases, because none of these bases are considered to be safe havens in a hurricane threat. The decision to sortie ships must be made 48-36 hours prior to the onset of destructive winds, and the cost of such a decision is significant. During the 1999 hurricane season, two examples stand out. Ships in two major Fleet Concentration Areas (Mayport, FL and Norfolk, VA) were sortied during Hurricane Floyd at an estimated cost of $17.2 million (Swaykos and Bosse 2000). By contrast, the decision to not sortie during Hurricanes Dennis and Irene saved the Navy over $13 million (Swaykos and Bosse 2000). On the civilian side, estimates of the costs incurred for hurricane preparations range anywhere from $155,000 to well over $1,000,000 for each nautical mile of U.S. coastline placed under a hurricane warning.

Above and beyond the estimated dollar-value costs, the primary motivation for improving the accuracy of tropical cyclone forecasting is safety of personnel and ships. One of the Commander, Naval Meteorology and Oceanography (METOC) Command missions is to provide global METOC services for safe and effective operations. A strategic outcome from this is “there will be no cheap kills from Mother Nature!”

(CNMOC 1997). As METOC personnel, we understand that "safety is fundamental to our mission and is the basis for virtually every function we perform" (CNMOC 1997). The stated requirement of the U.S. Navy is to reduce the 72-hour forecast track error (FTE) below 150 nautical miles.

Tropical cyclone (TC) forecasters must be able to provide timely and accurate information, specifically, track and outer wind structure (i.e., gale-force winds) that affords decision makers the ability to anticipate impacts, make informed decisions, and avoid losses posed by the threat of a TC. The National Hurricane Center (NHC) in Miami, FL, has the lead forecast responsibility for the Atlantic Ocean and Caribbean. Every six hours, the NHC issues a 72-hour track and intensity forecast for all tropical cyclones in the North Atlantic and eastern North Pacific basins. The Naval Atlantic Meteorology and Oceanography Command (NLMOC), Norfolk, VA, acts as the primary back-up for the NHC, and provides tailored guidance based on the NHC forecasts to the Fleet assets afloat and onshore.

The goal of this thesis is to examine the tropical cyclone applicability for the Atlantic and Caribbean areas of an improved methodology in tropical cyclone track forecasting called the Systematic and Integrated Approach to TC track forecasting (hereafter Systematic Approach). The Systematic Approach of Carr and Elsberry (1994) was originally developed and is most advanced in the western North Pacific region. The motivation for this thesis is that the Systematic Approach may assist the hurricane forecasters in achieving the Navy requirements for improved 72-h track forecasting.

B. SYSTEMATIC APPROACH BACKGROUND

1. Objective

The long-range objective of the Systematic Approach is to bring about quantitative and qualitative improvements in official TC track forecasts (Carr and Elsberry 1994). Quantitative improvements can be measured by lower average forecast track errors (FTE), official forecasts that are consistently better than the forecasts of the objective track forecast guidance available to the forecaster, and a reduction in the number of track forecasts that have very large FTEs. Although harder to measure, qualitative improvements are a function of the meteorological reasoning the forecaster applies in developing the official TC track forecast. The central thesis of the Systematic Approach is that the forecaster can formulate track forecasts that improve on the accuracy and/or consistency of the dynamical model or other objective guidance if he/she is equipped with: (i) a meteorological knowledge base of dynamically sound conceptual models that classify various TC-environment situations; (ii) a knowledge base of recurring TC track forecast errors attributed to various combinations of TC structure and environment structure, and the anticipated changes; and (iii) an implementing methodology or strategy for applying these two knowledge bases to particular TC forecast situations (Carr and Elsberry 1999).

2. Concept

Carr and Elsberry (1994) first introduced the Systematic Approach as a framework in which to apply research to operational forecasting of TCs in the western North Pacific. The fundamentals of the framework included a three-phase approach (Fig. 1) to operational forecasting of TCs. The numerical guidance evaluation Phase I

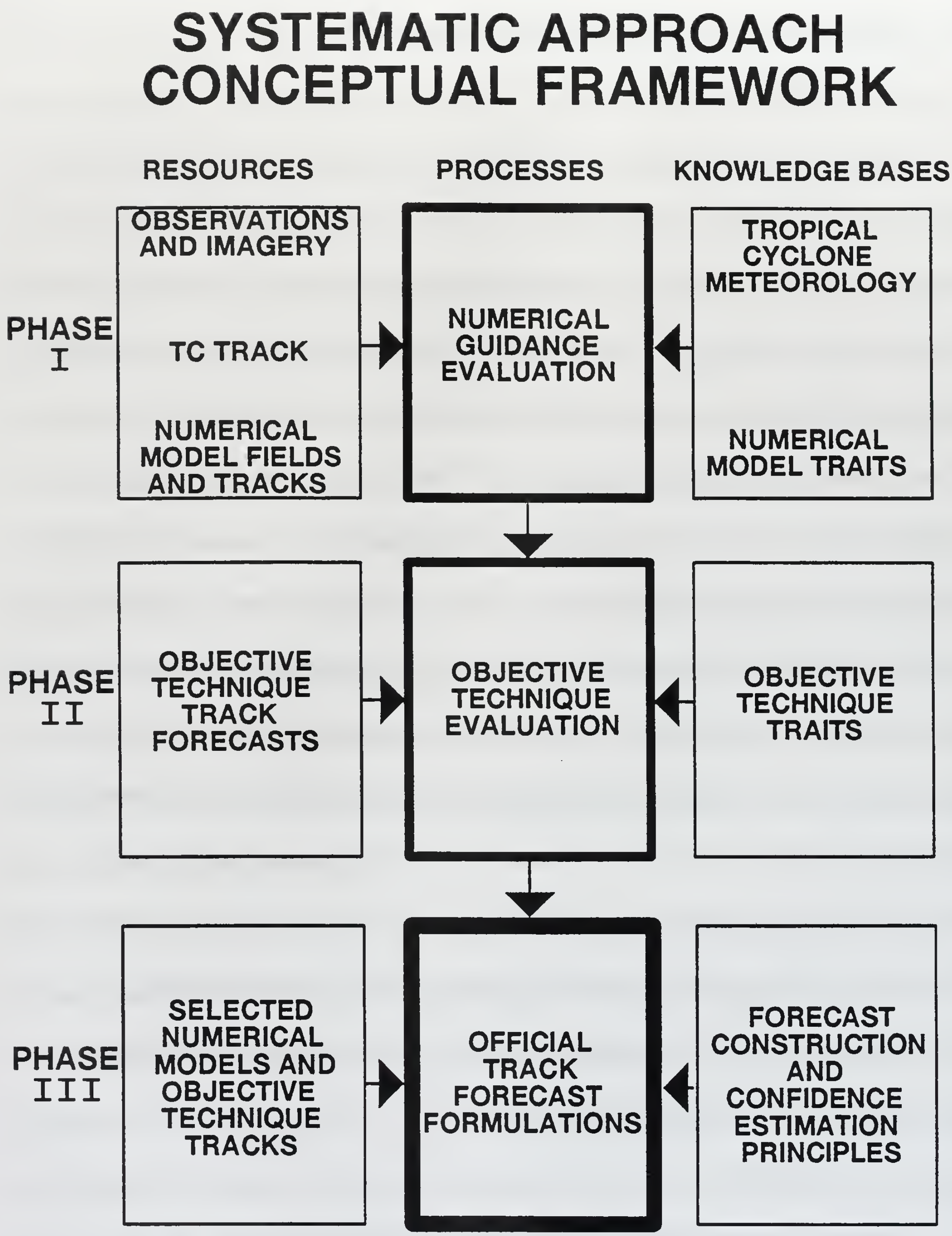

Figure 1. The overall conceptual framework of the Systematic Approach in three phases [from Carr and Elsberry (1999)].

combines an analysis of the numerical guidance, data, and satellite imagery with a knowledge base of TC-environment conceptual models and an understanding of numerical model traits. The TC forecaster's objective in Phase I is not to just accept a model track forecast, but to develop a conceptual understanding of the TC motion from a physical and dynamical perspective. In Phase II of Fig. 1, the TC forecaster takes the conceptual understanding of the situation that has been developed from Phase I and introduces objective technique forecasts, i.e., steering models or regression equation models, and their respective objective technique error traits. The objective of Phase II is to identify the tracks from dynamical models and/or objective techniques that are likely to be accurate based on past performance characteristics. The objective of the final Phase III of the Systematic Approach framework in Fig. 1 is to formulate an official track forecast based on an informed, selective consensus of the previously identified acceptable track guidance.

The most important components of the Systematic Approach are the TC Meteorological knowledge base and the Model Traits knowledge base (Carr and Elsberry 1999). The Model Traits knowledge base follows naturally from the assumption that the error characteristics of TC track forecasting models are not random, but rather, depend systematically on the particular meteorological situation responsible for the motion of the TC at any time. The Model Traits knowledge base of the Systematic Approach is comprised of the results of a systematic evaluation of the performance of available track forecast models in the various scenarios of TC-environment interaction described by the Meteorological knowledge base.

3. Atlantic Meteorological Knowledge Base

The four fundamental parts of the Meteorological knowledge base in the Systematic Approach for the Atlantic region are given in Fig. 2. The environment structure is classified in terms of synoptic patterns and regions. Synoptic patterns are classifications of the large-scale environment based on the presence and orientation of circulations such as cyclones and anticyclones. Synoptic regions are smaller regions within the synoptic patterns where variations in TC tracks are determined by the variations in environmental steering. Boothe et al. (1999) have identified three conceptual synoptic patterns and regions in the Atlantic basin (Fig. 3) that are common to other basins in which the Systematic Approach has been applied (i.e., western North Pacific, eastern and central North Pacific, and Southern Hemisphere). However, an additional pattern called the Upper low pattern has been recognized as being unique to the Atlantic basin.

The four synoptic patterns for the Atlantic basin are described by Boothe et al. (1999) and are only briefly summarized here.

(1) *Standard Synoptic Pattern*. In the Standard (S) synoptic pattern (Fig. 3, bottom), the axis of the subtropical ridge (STR) is oriented approximately east-west, although longitudinal variations in axis tilt may occur. The modifying influence of various midlatitude circulations may also distort the basic east-west orientation of the STR. A common occurrence is the presence of “breaks” in the STR axis that may occur in association with the passage of a midlatitude trough. Four synoptic regions are defined in association with the Standard synoptic pattern. Whereas the Equatorial Westerlies (EW) region has been observed in other basins, and may be possible in the Atlantic,

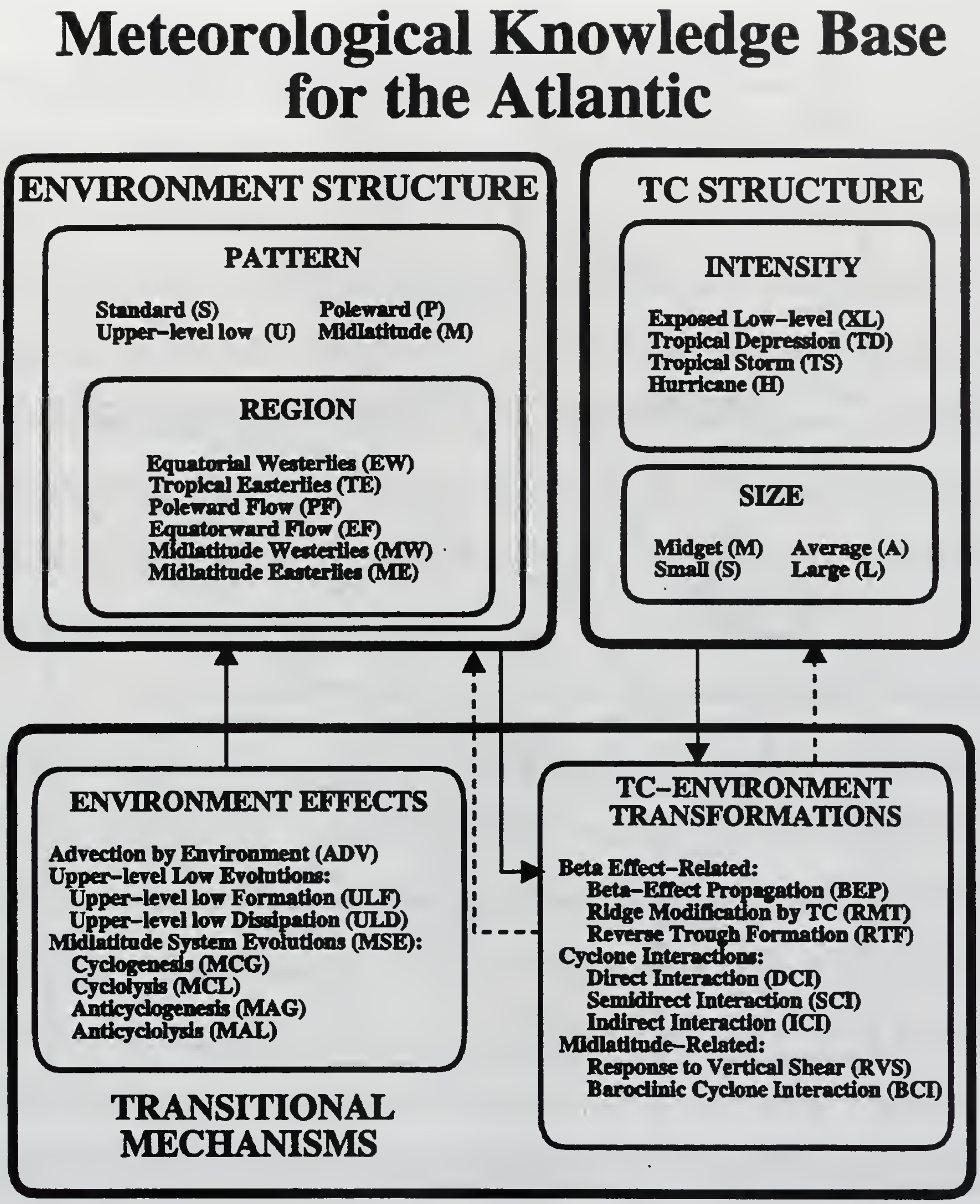

Figure 2. Meteorological knowledge base for application of the Systematic Approach to North Atlantic TCs (from Boothe et al. 1999).

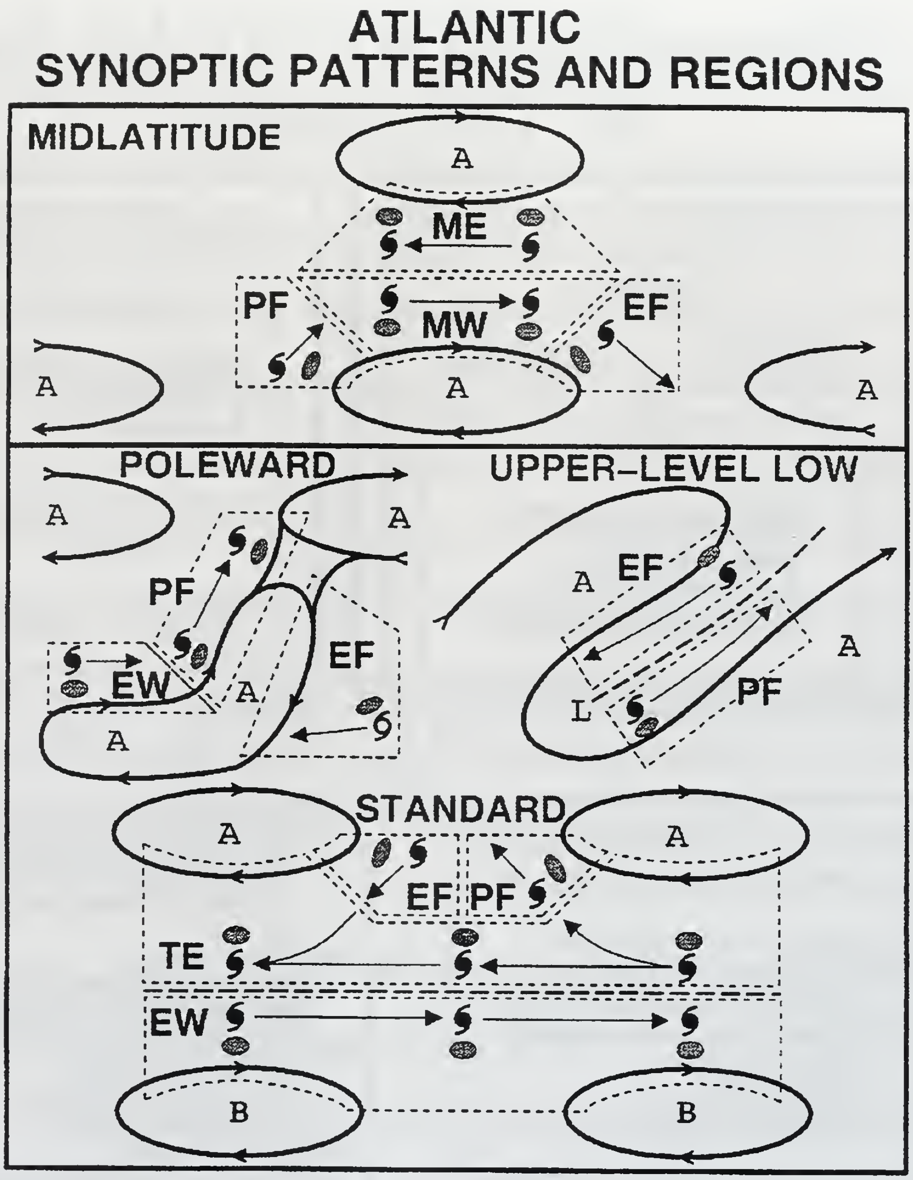

Figure 3. Environment structure conceptual models in the Meteorological knowledge base for the Atlantic (Fig. 2, upper left) in terms of four synoptic patterns (Midlatitude, Poleward, Upper, and Standard) and six synoptic regions (light dashed lines; see meanings of acronyms in Fig. 2). Whereas the three synoptic patterns in the lower panel generally apply while the TC is equatorward of the subtropical anticyclone axis, the Midlatitude pattern in the upper panel applies whenever the TC is poleward of the subtropical anticyclone axis. Thick solid streamlines represent the 500-mb environmental flow after removal of the TC circulation. The heavy dashed line in the lower portion represents the monsoon trough. Light solid arrows illustrate characteristic TC tracks. Isotach maxima relative to the TC positions are indicated by elliptical regions. These schematics depict the steering flow of TCs in terms of Anticyclones (A), Upper-tropospheric Low (L), and an equatorial Buffer (B) cell (from Boothe et al. 1999).

Boothe et al. (1999) did not find any Atlantic TCs in this synoptic region. The TCs in the Tropical Easterlies (TE) region have a basic westward-moving track. A TC in the Poleward Flow (PF) region is usually in a break in the STR caused by a midlatitude trough or other midlatitude circulation and the resulting TC track is toward the northwest. In the normal recurvature sequence, the TC would then cross the STR axis into the Midlatitude synoptic region to be described below. However, a delayed recurvature and movement into the Equatorward Flow (EF) region may occur if the western anticyclone cell builds eastward, or a midlatitude ridge blocks further poleward movement by the hurricane. A "stair step" appearance in the TC track of westward to northward and back to westward may occur in these situations.

(2) *Poleward Synoptic Pattern.* In the Poleward (P) synoptic pattern (Fig. 2, middle left), the environment is normally characterized by a predominant break in the STR axis poleward of the TC, and a meridionally-oriented peripheral anticyclone equatorward of the TC that extends from southwest to northeast to connect with the STR. Three distinct synoptic regions are associated with this pattern. In the Poleward Flow (PF) synoptic region, the TC is advected poleward in the flow on the western side of the peripheral anticyclone. The Equatorial Westerlies (EW) synoptic region is poleward of a long peripheral anticyclone that extends far equatorward. The resulting track in the P/EW pattern/region is eastward. The Equatorward Flow (EF) synoptic region is for a separate TC to the east that has an equatorward steering flow component as a result of Rossby wave dispersion from a western TC or other cyclonic circulation to the northwest. The characteristic track of a TC in the P/EF pattern/region is west-southwestward.

(3) *Upper-level Low Pattern.* A variation of the Upper-level low (U) synoptic pattern (Fig.3, middle right) was initially described by Kent (1995) as the Low pattern. The primary characteristic of this pattern is the presence of a mid-tropospheric low that has penetrated downward from an upper-tropospheric trough. Although weak steering circulations also extend to lower levels, it is usually the mid-tropospheric circulation that determines the steering flow of a TC in the U pattern. The TC in the Equatorward Flow (EF) region is between the mid-tropospheric trough and an anticyclone to the northwest. A TC in the Poleward Flow (PF) region is between the trough and an anticyclone to the southeast. Notice in Fig. 3 that an elongated trough is depicted with a northeast-southwest tilt. However, the upper-level low pattern may also occur with a more circular upper-level cyclone in place of the trough.

(4) *Midlatitude Synoptic Pattern.* The need for defining a Midlatitude (M) synoptic pattern was first recognized in the Atlantic basin because many Atlantic TCs continue to exist for significant periods after recurvature, and midlatitude circulations have much more spatial and temporal variability than in the western North Pacific. Thus, a multitude of variations in the TC-environmental structure may occur in the M synoptic pattern. Although a zonal subtropical anticyclone is depicted in Fig. 3 (top), other possible variations include a triangular STR circulation with a broad southern base, or a more meridional, oval-shaped anticyclone. The key determinant for a TC to be in the M pattern is that the TC is poleward of the STR axis. The Poleward (Equatorward) Flow synoptic region is similar to the region of the same name in the Standard pattern, but with the TC moving poleward (equatorward) on the northwest (northeast) side of a STR cell. The Midlatitude Westerlies (MW) synoptic region is characterized by eastward TC tracks

north of the STR. Finally, the relatively rare Midlatitude Easterlies (ME) region occurs when a midlatitude anticyclone located north of the TC is strong enough to advect the TC westward.

A key element of the Systematic Approach is to recognize transitional mechanisms and the TC-environment transformations (lower right portion of Fig. 2) that will lead to a transition in the environment structure. Because each such synoptic pattern/region transition is associated with a TC track change, it is important that the forecaster be equipped to recognize that a transition is (or will be) occurring. Equipping forecasters with the tools to recognize these changes in environment structure is a major goal of the Systematic Approach.

4. Evaluation Of Dynamical Models For The Western North Pacific

The purpose of the Carr and Elsberry (1999) study was the development of a Model Traits knowledge base of TC track forecast guidance in the western North Pacific. The objective was to identify principal error mechanisms in the dynamical models that are available to the TC forecasters at the Joint Typhoon Warning Center (JTWC), Pearl Harbor, HI. The study examined all 1997 TCs in the western North Pacific. Because the primary dynamical models available to the JTWC forecaster are the Navy Operational Global Atmospheric Prediction System (NOGAPS) and the Navy version of the Geophysical Fluid Dynamics Lab (GFDN) model, emphasis was placed on the traits of these two models. The longer range objective is to equip the JTWC forecaster to be able to make an official track forecast that is an informed selective or adjusted consensus of the dynamical model and/or objective technique guidance.

The key results regarding the NOGAPS model from the Carr and Elsberry (1999) study are: (i) Only six error mechanisms accounted for 84% of the large (>300 n mi at 72 h) track forecast errors; (ii) The NOGAPS model has a tendency to over-develop weak tropical disturbances in the vicinity of a TC; (iii) The NOGAPS model exhibited excessive growth of the TC and peripheral anticyclone in response to forcing by the Rossby wave train of another large cyclone; and (iv) Both over- or under-forecasts of the extratropical transition process can contribute to large TC track forecast errors.

A closely related goal of the Systematic Approach research activity is the development of a Systematic Approach Expert System (SAES). The track and field characteristics when large errors occurred are the basic elements of the Model Traits knowledge base that is the key intelligence in the SAES. Level I of the Model Traits knowledge base identifies the frequently occurring error mechanisms. Level II provides key field and track indicators of the frequently occurring error mechanisms. Levels III-V provide detailed illustrations, characteristics, and sample case studies of the various error mechanisms.

C. PURPOSE

The focus of prior Systematic Approach research has first been on the development of Meteorological and Model Traits knowledge bases for the western North Pacific. Carr and Elsberry (1999) have described eight conceptual models that explain most cases of large track errors by the NOGAPS and the GFDN models during the 1997 western North Pacific season. Dunnavan et al. (2000) have applied these same conceptual models to these U.S. Navy dynamical models as well as the United Kingdom Meteorological Office (UKMO) and the European Centre for Medium-range Weather

Forecasts (ECMWF) global models during the 1997 and 1998 western North Pacific seasons.

The purpose of this thesis is to expand the research in the North Atlantic basin via a documentation of the second major component of the Systematic Approach, which is a Model Traits knowledge base that describes how dynamical hurricane forecast track guidance performs in the North Atlantic Ocean. This Atlantic basin study is modeled after the western North Pacific study of Carr and Elsberry (1999). The hypothesis is that the dynamical models will have similar track error characteristics and that cases with large errors in Atlantic TC track forecasts may be explained with the same eight conceptual models and with similar relative frequencies. As such, the goal of this thesis is to assist the NLMOC forecasters in providing improved hurricane track forecasts for the Fleet. In particular, this thesis will focus on the identification and analysis of instances when highly erroneous TC track forecasts have been made by one or any combination of the three models included in the study. This documentation is a necessary step to successfully recognize highly erroneous dynamical model track forecasts on a real-time basis, and either discard or greatly modify such objective forecasts when formulating the official track forecast. Guided by such knowledge, the forecaster will be able to formulate a track forecast that reflects an informed adjusted or selective consensus of the remaining dynamical model tracks, as opposed to using an indiscriminate simple consensus of all available track guidance.

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II. APPROACH

A. METHODOLOGY

This study examines large Atlantic TC track errors made by the dynamical models for the 1997 and 1998 seasons. The threshold for a model error to be defined as "large" in the Atlantic is reduced to 250 n mi from 300 n mi in the western North Pacific to reflect the lower average model errors in the Atlantic. The database for this study consists of the NOGAPS, UKMO, and ECMWF track and forecast fields for all 1997 and 1998 North Atlantic hurricanes. The analysis is limited to 1997-1998 as these are the only years in which at least three models were available. Some limited description will be provided on the traits of other objective hurricane forecasting techniques employed by NLMOC, as well as other numerical models.

The database did not include the GFDL forecast fields for 1998. A preliminary review of the GFDL large FTEs during 1997 indicated too small of a sample to be of any significant contribution to this study. During the 1998 hurricane season, the National Centers for Environmental Prediction (NCEP) Aviation model, which provides the initial and boundary conditions for the GFDL regional model, affected the GFDL hurricane track forecasts in a detrimental way.

The NOGAPS spectral forecast model, which has a horizontal resolution of ~ 75 km, was upgraded from version 3.4 to 4.0 on 24 June 1998. As the primary change was only to increase the number of vertical levels from 18 to 24, significant changes in model tendencies between the 1997 and 1998 track forecasts are not expected. The NOGAPS uses 13 synthetic observations to define the TC circulation in the data assimilation cycle. Tracking of the TC center in the NOGAPS prediction is via the 1000-mb wind center.

The present UKMO global model has 30 vertical levels and a horizontal resolution of about 60 km. The center of the TC is located by searching for the local maximum of relative vorticity at 850 hPa. A surface-fitting technique is then applied to accurately locate the tropical cyclone center.

The ECMWF model has 50 vertical levels and an effective horizontal resolution of about 40 km. Because the ECMWF does not insert synthetic observations in the analysis as in the NOGAPS and UKMO models, the initial position errors are typically larger. The tracks for the ECMWF forecasts have been kindly provided by Dr. M. Fiorino, who developed a tracking routine similar to the NOGAPS procedure. Without synthetic observations, the ECMWF tracking routine may have a tendency to lose the vortex prior to 72 h. No attempt has been made to manually extract a center from the predicted fields if the ECMWF (or the NOGAPS or UKMO) tracker loses the vortex prior to 72 h. Whereas the NOGAPS and UKMO models are integrated twice a day, the ECMWF model is integrated only once a day at 1200 UTC and is generally not available until about 18 h later. The poor timeliness and non-availability of the high resolution ECMWF predicted fields hinder the use of these tracks for operational use.

B. TRACK ERRORS OVERVIEW

The distribution of the 72-h NOGAPS, UKMO, and ECMWF forecast track errors (FTE) for the 1997 and 1998 North Atlantic hurricane seasons are shown in Fig. 4. Notice the histograms of the NOGAPS, UKMO, and ECMWF track errors are not normal distributions. Rather, the distributions are skewed toward the larger FTEs that pose a serious problem for the forecaster. The largest 72-h FTEs are 939, 698, and 848 n mi for

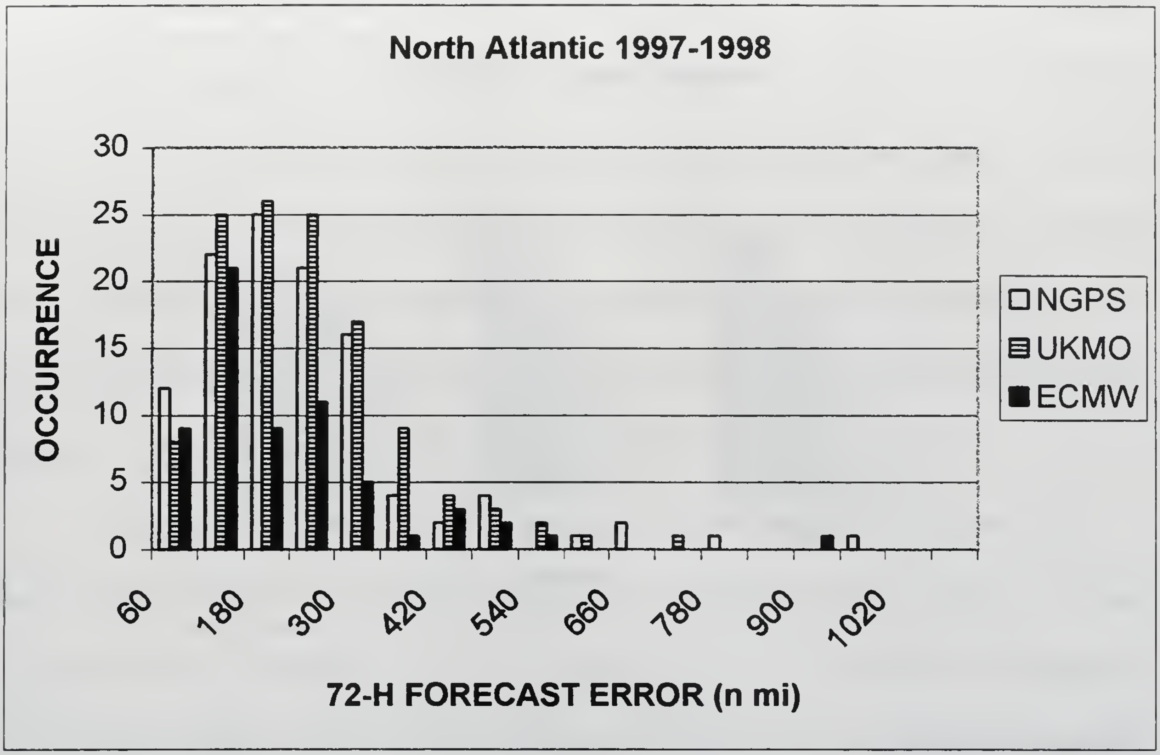

Figure 4. Frequency of occurrence of 72-h track errors for the NOGAPS, UKMO, and ECMWF forecasts of North Atlantic TCs during the 1997 and 1998 hurricane seasons.

the NOGAPS, UKMO, and ECMWF models, respectively. The average 72-h FTEs are 198, 205, and 175 n mi for the NOGAPS, UKMO, and ECMWF models, respectively. The average 24-72 h FTEs for the three models are depicted in Fig. 5. Notice that the UKMO model is superior to the other two models at 24 h and 48 h. The reason for defining a 72-h FTE > 250 n mi as a highly erroneous track forecast is evident from Figs. 4 and 5. The percentage of 72-h forecasts with a 250 n mi or greater FTE is 23% for NOGAPS, 26% for UKMO, and 19% for ECMWF. A FTE of 250 n mi is 166% the magnitude of the average 72-h FTE goal of 150 n mi that the NLMOC customers require. The percentage of 72-h forecasts with a 150 n mi or greater FTE is 58% for NOGAPS, 61% for UKMO, and 48 % for ECMWF.

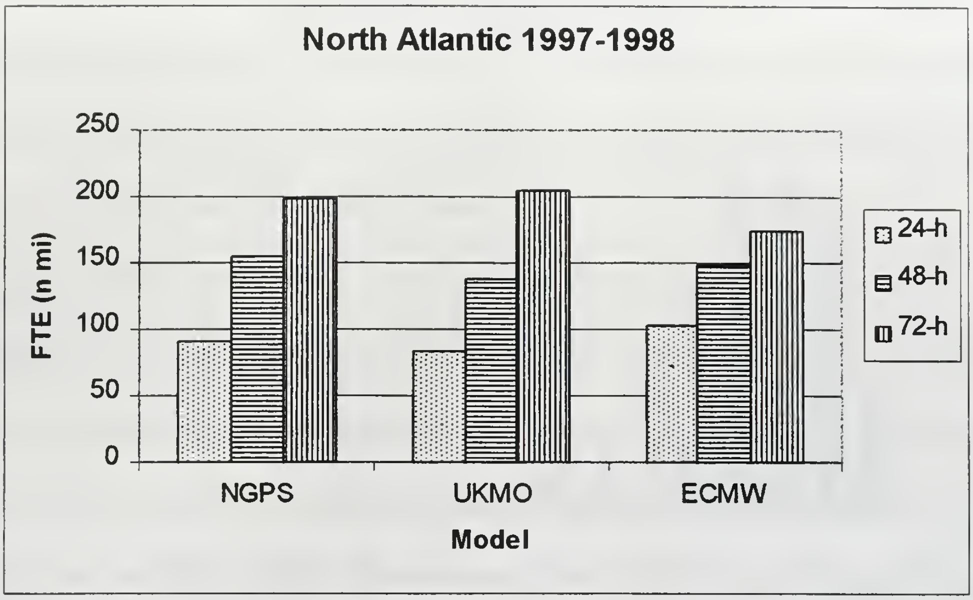

Figure 5. Average FTE for the NOGAPS, UKMO, and ECMWF during the 1997 and 1998 hurricane seasons.

To create a homogeneous sample, the FTE statistics are calculated for those cases in which both the NOGAPS and UKMO 72-h forecasts are available. For the 92 forecasts in which the two models tracked the TC to 72 h, the average NOGAPS and UKMO 72-h FTEs were 197 and 205 n mi, respectively. The ECMWF forecasts are not included in the homogenous sample since they are only available at 1200 UTC, which would decrease the sample by at least a factor of two. That is, only 39 cases were available in which all three models produced a 72-h forecast for the same initial integration time. The average 72-h FTEs for these 39 forecasts were 178, 204, and 144 n mi for NOGAPS, UKMO, and ECMWF, respectively. Based on a student t-test statistical analysis, the ECMWF average FTE is significantly smaller than that of UKMO (NOGAPS) at the 99% (at least 90%) confidence value.

For each forecast time at which any of the models had a FTE greater than 250 n mi, a subjective analysis as in Carr and Elsberry (1999) was conducted of the forecast fields of all three dynamical models. In addition, visible, infrared, and water vapor imagery was also a part of the examination. The objective was to determine if a plausible physical mechanism could be identified to account for the large FTE. The results of this analysis will be the basis for a NOGAPS, UKMO, and ECMWF Model Traits knowledge base as in Carr and Elsberry (1999) for the western North Pacific.

The results of the above error analysis process are listed by TC number and forecast initial time for the NOGAPS, UKMO, and ECMWF models in Tables 1, 2, and 3, respectively. The meanings and frequencies of the "cause" acronyms in these tables are provided in Table 4. An overview is presented here to provide a perspective on the relative frequency from various error sources.

Erroneous binary cyclone interaction (Table 4, rows DCI through ICIW) accounted for 9 (31%), 9 (28%), and 3 (23%) of poor 72-h forecasts for the NOGAPS, UKMO, and ECMWF models, respectively. Notice the NOGAPS and UKMO models were the only models degraded by Excessive-Direct Cyclone Interaction (E-DCI). Based on historical records (Neumann 1993), only on a few occasions are multiple TCs present at the same time in the North Atlantic. As will be demonstrated later, the cases of E-DCI in this study normally occurred with a false tropical cyclone in the forecast fields. The only occurrence of E-DCI with another TC was for Hurricane Karl during 1998. By contrast, the ECMWF track forecast was the only model degraded by Semi-direct Cyclone Interaction (SCI).

Table 1. All NOGAPS 72-h track forecasts for North Atlantic TCs during 1997-1998 that resulted in a forecast track error (FTE; n mi) exceeding 250 n mi. The meanings of the acronyms in the "Cause" columns are provided in Table 4. The appearance of ????? in the "Cause" column indicates that a dynamical explanation for the large FTE could not be readily discerned.

NOGAPS 72-H FORECASTS EXCEEDING 250 N MI IN 1997-1998							
1997				1998			
TC	DATE	FTE	CAUSE	TC	DATE	FTE	CAUSE
01L	070100	433	E-RVS	02L	082500	252	?????
03L	071312	469	E-DCI	02L	082712	556	E-RVS
04L	071712	264	E-MAG	04L	083100	347	E-RVS
06L	090712	270	E-DCI	06L	090900	626	E-ICIE
				07L	091600	373	E-RVS
				07L	092012	277	?????
				07L	092600	280	E-MAG
				09L	092100	290	E-DCI
				09L	092112	294	E-DCI
				10L	092700	287	?????
				10L	092800	412	E-DCI
				11L	092400	434	E-DCI
				11L	092412	612	E-DCI
				11L	092500	939	E-DCI
				13L	102712	413	E-RMT
				13L	102800	432	E-RMT
				13L	102812	351	E-RMT
				13L	102900	300	E-RMT
				13L	102912	353	E-RMT
				13L	103000	304	E-RMT
				13L	103012	278	E-RMT
				13L	110112	251	I-TCS
				13L	110200	444	E-RMT
				14L	112712	264	I-BCI
				14L	112800	739	I-BCI

Ridge Modification by a TC (RMT) and Reverse Trough Formation (RTF) are a manifestation of the beta effect and involve the development of a peripheral anticyclone eastward and equatorward of the TC that contributes to a poleward motion of the TC (see Poleward pattern in Fig. 3). Erroneous predictions of these two phenomena together contribute to 7 (24%) of the NOGAPS and 7 (22%) of the UKMO degraded track

Table 2. As in Table 1, except for the UKMO 72-h track forecasts.

UKMO 72-H FORECASTS EXCEEDING 250 N MI IN 1997-1998					
1997 TC DATE	FTE	CAUSE	1998 TC DATE	FTE	CAUSE
01L 070100	480	E-MCG	02L 082000	365	?????
06L 090512	270	I-RMT	02L 082012	385	E-RMT
06L 090900	347	I-BCI	02L 082700	252	E-RVS
06L 091112	252	?????	02L 082712	308	E-RVS
06L 091200	353	E-BCI	04L 082612	262	E-RMT
06L 091212	698	E-BCI	04L 082712	280	E-RMT
			04L 082812	280	E-RMT
			04L 082912	285	E-RMT
			04L 083000	270	E-ICIE
			07L 091512	299	E-RVS
			07L 092000	337	?????
			07L 092100	274	?????
			09L 092012	357	E-DCI
			09L 092100	353	E-DCI
			09L 092112	528	E-DCI
			11L 092412	322	E-DCI
			11L 092500	460	?????
			12L 100600	373	E-MCG
			12L 100612	281	E-BCI
			13L 102200	344	E-DCI
			13L 102500	265	E-RTF
			13L 102700	427	E-DCI
			13L 102712	312	E-DCI
			13L 102800	281	E-DCI
			14L 112712	544	E-BCI
			14L 112812	522	E-BCI

forecasts during 1997-98. Of special note, the ECMWF model had no poor forecasts attributed to either phenomenon, which may be a reflection that this model has more compact vortices that are less likely to create RMT and RTF situations.

Response to Vertical wind Shear (RVS) and Baroclinic Cyclone Interaction (BCI) usually involve interactions with midlatitude circulations. A RVS event will tend to reduce the warm core aloft and decrease the intensity of the TC, which leads to a lowering of the environmental steering layer such that the translation speed of the TC

Table 3. As in Table 1, except for the ECMWF 72-h track forecasts.

ECMWF 72-H FORECASTS EXCEEDING 250 N MI IN 1997-1998							
1997				1998			
TC	DATE	FTE	CAUSE	TC	DATE	FTE	CAUSE
06L	091212	261	E-BCI	01L	072712	396	E-MCG
				01L	072812	392	E-MCG
				01L	072912	250	E-MCG
				02L	082712	345	E-MCG
				04L	082412	266	E-ICIE
				04L	082512	286	E-ICIE
				10L	092312	296	I-TCS
				10L	092512	488	I-TCS
				10L	092712	369	E-MCG
				11L	092412	427	E-SCIW
				12L	100612	848	I-BCI
				13L	110112	458	I-TCS

would be expected to decrease. A BCI event influences the TC motion by aiding in the deepening, or at least maintaining, the strength of the TC as it undergoes extratropical transition. Erroneous prediction of these two phenomena together contributed to 6 (21%) NOGAPS, 9 (28%) UKMO, and 2 (15%) of ECMWF degraded track forecasts. Whereas the NOGAPS model suffered from I-BCI, the majority of UKMO poor track forecasts were attributed to E-BCI.

The TC track errors associated with the influence of Midlatitude System Evolutions (MSE) relate the changes in environmental steering of the TC to the influence of midlatitude circulation movement and structure. These MSE are further classified into Midlatitude CycloGenesis (MCG), Midlatitude AnticycloGenesis (MAG), Midlatitude

Table 4. Meanings and frequencies of the causes of large NOGAPS, UKMO, and ECMWF forecast track errors in the North Atlantic during 1997-98. If two numbers are listed, the first (second) is the number of times the phenomenon occurred excessively (insufficiently) in the model and corresponds to the E (I) prefixes in Tables 1, 2, and 3.

CAUSE OF NOGAPS, UKMO, OR ECMWF 72-H FORECAST TRACK ERRORS GREATER THAN 250 N MI		Number of Forecasts		
Phenomenon Name	Acronym	NOGAPS	UKMO	ECMWF
Direct Cyclone Interaction	DCI	8-0	8-0	0-0
Semi-Direct Cyclone Interaction	SCI			
SCI on Western TC	SCIW	0-0	0-0	1-0
SCI on Eastern TC	SCIE	0-0	0-0	0-0
Indirect Cyclone Interaction	ICI			
ICI on Eastern TC	ICIE	1-0	1-0	2-0
ICI on Western TC	ICIW	0-0	0-0	0-0
Ridge Modification by TC	RMT	7-0	5-1	0-0
Reverse Trough Formation	RTF	0-0	1-0	0-0
Response to Vertical Wind Shear	RVS	4-0	3-0	0-0
Baroclinic Cyclone Interaction	BCI	0-2	5-1	1-1
Midlatitude Systems Evolutions	MSE			
Midlatitude CycloGenesis	MCG	0-0	2-0	5-0
Midlatitude CycloLysis	MCL	0-0	0-0	0-0
Midlatitude AnticycloGenesis	MAG	2-0	0-0	0-0
Midlatitude AntiCyclosis	MAL	0-0	0-0	0-0
Tropical Cyclone Initial Size	TCS	0-2	0-0	0-3
All discernible causes		26	27	13
Not discernible or explainable		3	5	0
All cases		29	32	13

AnticycloLysis (MAL), and Midlatitude CycloLysis (MCL). The overall MSE error sources account for 2 (7%) NOGAPS, 2(6%) UKMO, and 5 (38%) ECMWF large track forecast errors, respectively. A majority of the poor forecasts attributed to MSE occurred as a result of E-MCG.

Incorrect Tropical Cyclone initial Size (TCS) was primarily responsible for the degradation of 3 (23%) ECMWF forecasts. These large errors were associated with a too small initial TC size in the model, which may not be surprising since no synthetic TC observations are added to the ECMWF initial conditions and inadequate observations

may be available to define the vortex. One of the errors was associated with too small initial intensity during the final stages of former Hurricane Mitch as it moved offshore of Central America. The NOGAPS model also experienced the same phenomena twice (7%) with Hurricane Mitch.

Three (10 %) NOGAPS and 5 (16 %) UKMO forecasts with large 72-h errors were considered to have no discernible physical explanation. Five of these eight forecasts had FTEs of less than 300 n mi, and the largest forecast error was 460 n mi. Recall that the threshold defining a poor 72-h FTE had been lowered from 300 n mi to 250 n mi since the average FTE is normally lower in the North Atlantic. The average FTE when a non-discernible error occurred for the NOGAPS and UKMO models were 272 and 338 n mi, respectively.

The error mechanisms in the rows DCI through BCI of Table 4 are related to TC-Environment Transformations in the Meteorological knowledge base (Fig. 1, lower right), and in each case the TC circulation interacts significantly with the surrounding environment. These mechanisms accounted for 55%, 47%, and 38 % of the poor NOGAPS, UKMO, and ECMWF track forecasts, respectively. Furthermore, the misrepresentation of phenomena that depend sensitively on the fidelity with which the structure of the TC is represented in the model was always excessive in nature, e.g., E-DCI.

The error mechanisms in rows MCG through MAL in Table 4 involve large-scale midlatitude processes to which the TC is a comparatively passive respondent. These mechanisms accounted for 33%, 38%, and 31% of the poor NOGAPS, UKMO, and

ECMWF track forecasts, respectively. Eighty (twenty) percent of these midlatitude-related error mechanisms were excessive (insufficient) in nature.

The results of this error analysis have important ramifications for operational hurricane forecasting and dynamical hurricane forecast model development. For the North Atlantic forecaster, it means that particular attention should be paid to evaluating the dynamical hurricane model forecasts for indications of an excessive TC interaction with the environment. As in the previous research for other basins, numerical modeler's efforts should also focus on achieving improved model representations of TC structure and interaction with the environment.

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III. CASE STUDY ANALYSIS

This chapter addresses the error mechanisms cited in Table 4 as causes of large NOGAPS, UKMO, and/or ECMWF FTEs. Each sub-section includes a conceptual depiction and description of the error mechanisms, a brief description of the frequency and important characteristics of the phenomenon, one or more illustrative case studies, and a brief summary. The primary purpose of the case studies is to illustrate the important aspects and variations of the different error mechanisms. The key illustration in the case studies is a comparison/verification figure that uses an 8- or 12-panel, 2-page spread to depict: (i) NOGAPS, UKMO, and/or ECMWF track forecasts, and other numerical models available to the NLMOC; (ii) NOGAPS, UKMO, and/or ECMWF forecast fields that are associated with these illustrated track forecasts, and (iii) NOGAPS or UKMO analyses at the times the NOGAPS, UKMO, and ECMWF forecast fields verify. During the course of the discussion, some attention will be given to clues that the forecaster can use in real-time to detect and account for expected degradations to dynamical model track forecasts.

A. BINARY CYCLONE INTERACTION

According to Table 4, all three of the modes of binary cyclone interaction (i.e., direct, semi-direct, and indirect) defined by Carr et al. (1999) were identified as causes for erroneous track forecasts by at least one of the global dynamical models included in this study. Because erroneous direct cyclone interaction (DCI) was responsible for 16 of the erroneous NOGAPS and UKMO forecasts of Atlantic TCs during 1997 and 1998, this phenomenon is thoroughly discussed and illustrated.

1. Direct Cyclone Interaction (DCI)

a. Description

Recall from Table 4 that Excessive Direct Cyclone Interaction (E-DCI) was identified as a cause for erroneous 72-h NOGAPS and UKMO track forecasts models eight times each. The ECMWF model was not affected by E-DCI. A conceptual model of the E-DCI phenomenon is shown in Fig. 6. An E-DCI event occurs when a numerical model forecasts false (i.e., does not occur in reality) or excessive cyclonic orbiting of a TC with a nearby cyclone. In addition, the model may forecast a merger of the TC with the nearby cyclone, and this new circulation will often be larger in size than the analyzed TC. The second cyclone may be another TC, a real or false non-developing tropical disturbance, or a deep upper-level cyclone that originates in the midlatitude region. The E-DCI phenomenon occurs due to mutual advection and shearing by one or both cyclonic circulations. Carr and Elsberry (1999) identified several variations of the E-DCI error mechanism that focused on the model representation of the TC size and/or depth, a mislocation of the TC and/or second cyclone, or self-interaction between the TC in the first-guess field and the synthetic TC observations.

b. Frequency and Characteristics

In the 1997-1998 sample of NOGAPS, UKMO, and ECMWF track forecasts, 16 periods (based on model initialization time) involving six hurricanes were identified when E-DCI occurred sometime during the model integration (Table 5). As a comparison, the western North Pacific study by Carr and Elsberry (1999) found E-DCI was responsible for about 36% and 31% of excessive FTEs for the NOGAPS and GFDN, respectively. Six of the eight E-DCI periods occurred when the TC was classified as

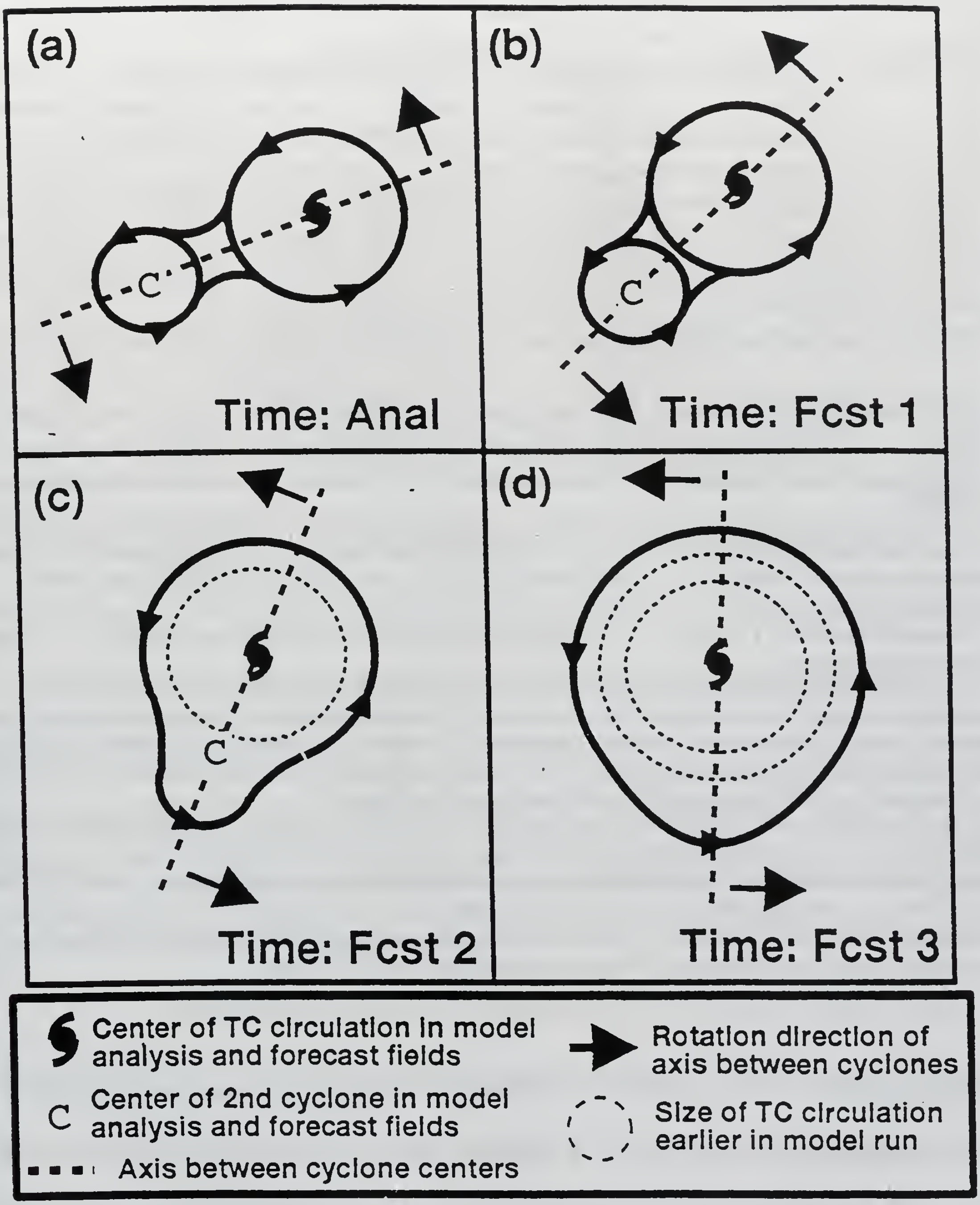

Figure 6. A conceptual model of Direct Cyclone Interaction (DCI) in which a TC circulation interacts with another cyclone (C) to cause a counter-clockwise (Northern Hemisphere) rotation of the axis between the cyclone centers (heavy dashed line) and a possible merger of the two cyclones in which the combined circulation becomes larger with time (panels c and d). The TC may also be the smaller of the two cyclones, or the model may be applied to two TCs of similar sizes in which the tracks of both TCs will be affected [from Carr and Elsberry (1999)].

Table 5. Cases of model-predicted Excessive Direct Cyclone Interaction (E-DCI) in the North Atlantic during the 1997 and 1998 hurricane seasons.

TC No	Starting times of affected model runs[1]	Synoptic Environment of TC	Intensity during interaction[2]	Nature of second cyclone[3]	Location Of second Cyclone[4]	Models affected[5]
97-01L	Jul 13/12	S/PF	30 → 40	ULC	SW	N
97-06L	Sep 07/12	P/PF	75 → 110	FTC	SW	N
98-09L	Aug 20/12 → 21/12	S/TE → P/PF	30 → 70	FTC	S	U, N
98-10L	Sep 28/00	S/PF → M/PF	80 → 30	ETC		N
98-11L	Sep 24/00 → 25/00	M/MW → M/EF	35 → 90 → 60	IVAN, JEANNE	E, SE	N
98-11L	Sep 24/12	M/EF	40 → 90	IVAN		U
98-13L	Oct 22/00	S/TE → P/PF	25 → 100	FTC	SW	U
98-13L	Oct 27/00 → 28/00	S/TE → S/EF	140 → 75	FTC	SW	U

Footnotes:

1. The date and times (UTC) indicated in column 2 give the starting times of the first and last model run affected noticeably by E-DCI. In the case of Ivan (98-09L) three model runs were affected by E-DCI and had starting times of 1200 UTC 20 August, 0000 UTC 21 August, and 1200 UTC 21 August 1998, respectively.
2. Intensities in column 4 are in kt, and correspond to the values at the beginning and end of the DCI period shown in the column.
3. PTC = Probable Tropical Circulation, or FTC = False Tropical Circulation. A probable (false) assignment is made if the existence of the disturbance is (is not) supported by discernible convection in satellite imagery. ETC = Extra-Tropical Cyclone. ULC = Upper Level Circulation, which is usually a cut-off low originating from the mid-latitudes; ##L = a NHC-designated TC that is involved in the E-DCI; pre = a precursor to a NHC-designated TC that is involved in the E-DCI.
4. The set of letters is the compass direction from the TC involved in the DCI when the interaction begins. The presence of an asterisk indicates that a significant error in the position of the TC (relative to the best-track position) toward the location of the second cyclone appeared to cause or influence the E-DCI.
5. N = Navy Operational Global Atmospheric Prediction System (NOGAPS); G = Geophysical Fluid Dynamics Laboratory TC Model; U = United Kingdom Meteorological Office model (UKMO); E = European Centre for Medium-range Weather Forecasting (ECMWF) model.

being in the S/TE, S/PF, or P/PF pattern/region, or a transitional state between two of these pattern/region combinations. In addition, the only two cases of E-DCI in which a second TC was actually present involved TC Karl, which was in the midlatitude region. Thus, the forecaster will usually be able to limit his/her focus on the E-DCI phenomenon to the periods when the TC is moving westward or has recently turned poleward. The case studies that follow will show that E-DCI is reasonably easy to identify with the proper model fields and an understanding of what clues identify E-DCI.

c. *Case Studies*

(1) Hurricane Mitch (98-13L). For this hurricane, the UKMO track forecasts were affected by E-DCI for three model integrations initiated at 0000 UTC 27 October, 1200 UTC 27 October, and 0000 UTC 28 October 1998 (Table 5). At the model integration time of 0000 UTC 27 October, Hurricane Mitch is near 17.2°N, 83.8° W with an intensity of 140 kt. The TC is translating toward 287° at 7 kt and is in a transition period from the S/TE synoptic pattern/region to the S/EF pattern/region. The center of Mitch meandered near the coast of Honduras on 27 and 28 October and then made landfall on 29 October. The UKMO tracks for the three model integrations are shown in Fig. 7. The initial forecast track (Fig. 7a) is far west of the best-track with a 48-h FTE of 251 n mi that increases to 427 n mi by 72 h. The UKMO model forecast continues the trend of a west or northwest track error in the subsequent forecast integrations of 1200 UTC 27 October and 0000 UTC 28 October (Figs. 7b and 7c, respectively). By comparison, the NOGAPS forecast for 0000 UTC 27 October is north of the best-track with a 72-h FTE of 243 n mi.

A comparison/verification of the UKMO 500-mb height fields and the 850-mb relative vorticity from integrations initiated at 0000 UTC 27 October is given in Figs. 8 and 9 to provide a context for the period of E-DCI. In the verifying analysis (Fig. 8b), a trough is to the southwest of Mitch with a secondary center near 8°N, 103°W. At 0000 UTC 29 October (Fig. 8c), this trough is somewhat weakened and appears less connected to Mitch as a ridge builds from the north and south, and the secondary cyclone is slightly west of its previous position. At 0000 UTC 30 October (Fig. 8d), the secondary cyclone has moved farther westward and a col now separates the TC from the

western cyclone. The UKMO 24-h forecast (Fig. 8f) maintains a trough axis between Mitch and the closed upper-level low to the southwest. In addition, the UKMO 500-mb 24-h and 48-h (Fig. 8g) forecasts depict a stronger isotach maximum to the northwest of the TC that is consistent with the slight southwestward turn in the forecast track. The 72-h UKMO forecast (Fig. 8h) has a weaker trough as the ridge builds from the north.

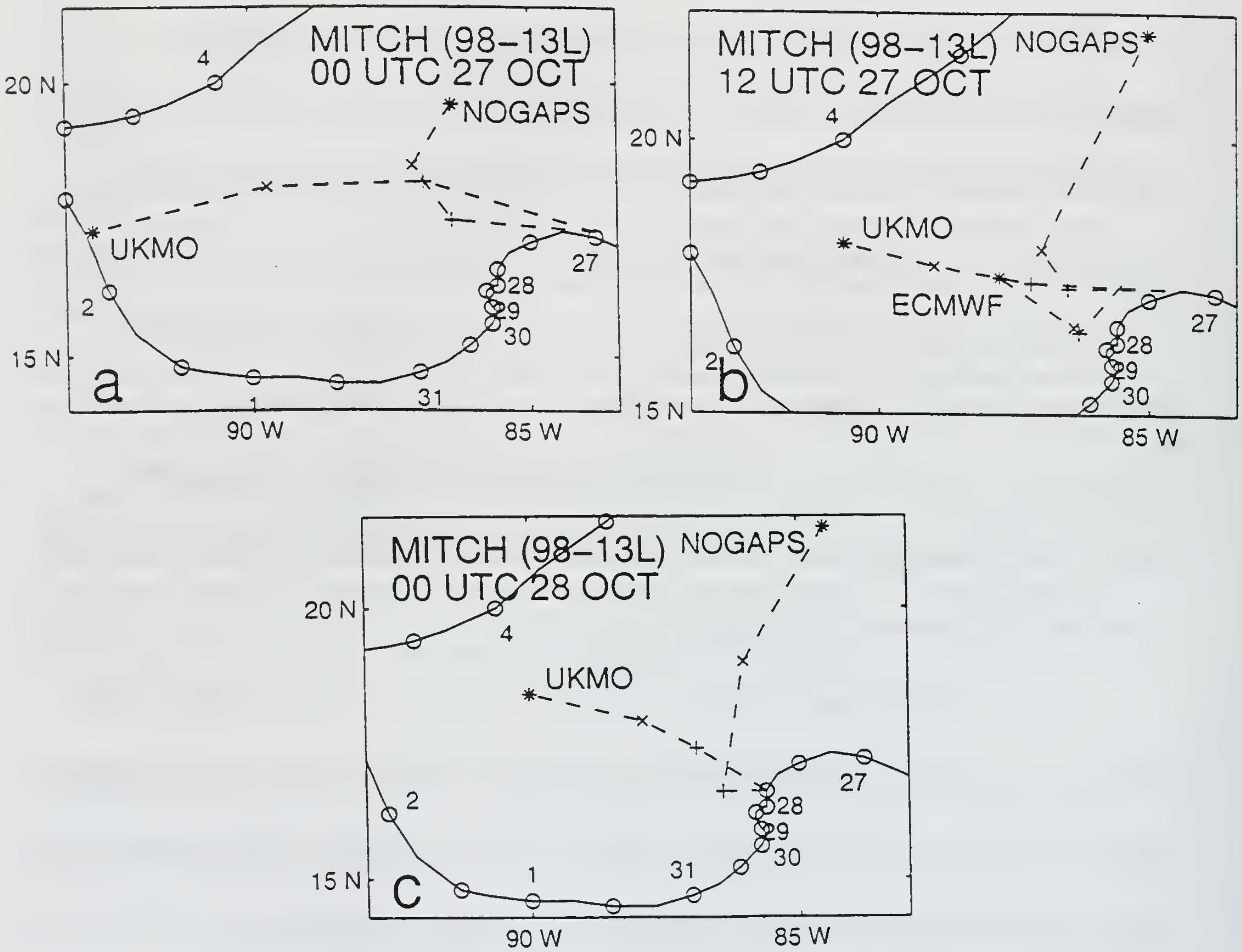

Figure 7. Best-track (circles each 12 h) and selected forecasts (see inset) of TC Mitch (98-13L) initiated at (a) 0000 UTC 27 October, (b) 1200 UTC 27 October, and (c) 0000 UTC 28 October 1998. Asterisks are the verifying position for the 72-h forecast for models initiated at 0000 UTC 27 October, 1200 UTC 27 October, and 0000 UTC 28 October, respectively.

In the 850-mb relative vorticity analyses (Fig. 9, panels b-d), a region of higher positive vorticity is to the southwest of, and remains distinct from, the TC. No significant change of the relative vorticity pattern occurs in the analysis fields from 0000 UTC 28 October to 0000 UTC 30 October. The 24-h UKMO 850-mb relative vorticity forecast (Fig. 9f) has a larger horizontal extent in the vorticity field to the southwest of the TC. By 48 h (Fig. 9g), the lobe of positive relative vorticity and the TC begin to rotate cyclonically around each other. By 72 h (Fig. 9h), the TC and secondary region of positive relative vorticity merge. The subsequent model integrations initiated at 1200 UTC 27 September and 0000 UTC 28 September (not shown) continue the trend of a counter-clockwise rotation in the vorticity pattern. The cyclonic curvature of the UKMO track and the interaction of Mitch with the lobe of positive vorticity to the southwest provide an indication to the forecaster of the E-DCI error mechanism.

(2) Hurricane Jeanne (98-10L). For this hurricane, the NOGAPS track forecasts were affected by E-DCI for the model integration at 0000 UTC 28 September 1998 (Table 5). At this time, Hurricane Jeanne is located near 28.8°N, 41.2° W with an intensity of 65 kt. The TC is translating toward 010° at 17 kt and is in a transition from the S/PF pattern/region to the M/PF pattern/region. In addition, the TC will have a transition to the M/MW pattern/region during the integration, and will become extratropical on 1 October. The NOGAPS forecast track (Fig. 10a) is far left and poleward of the best-track with a 48-h FTE of 253 n mi that increases to 412 n mi by 72 h. By comparison, the UKMO forecast is slightly left and slow relative to the best-track with a 72-h FTE of 175 n mi.

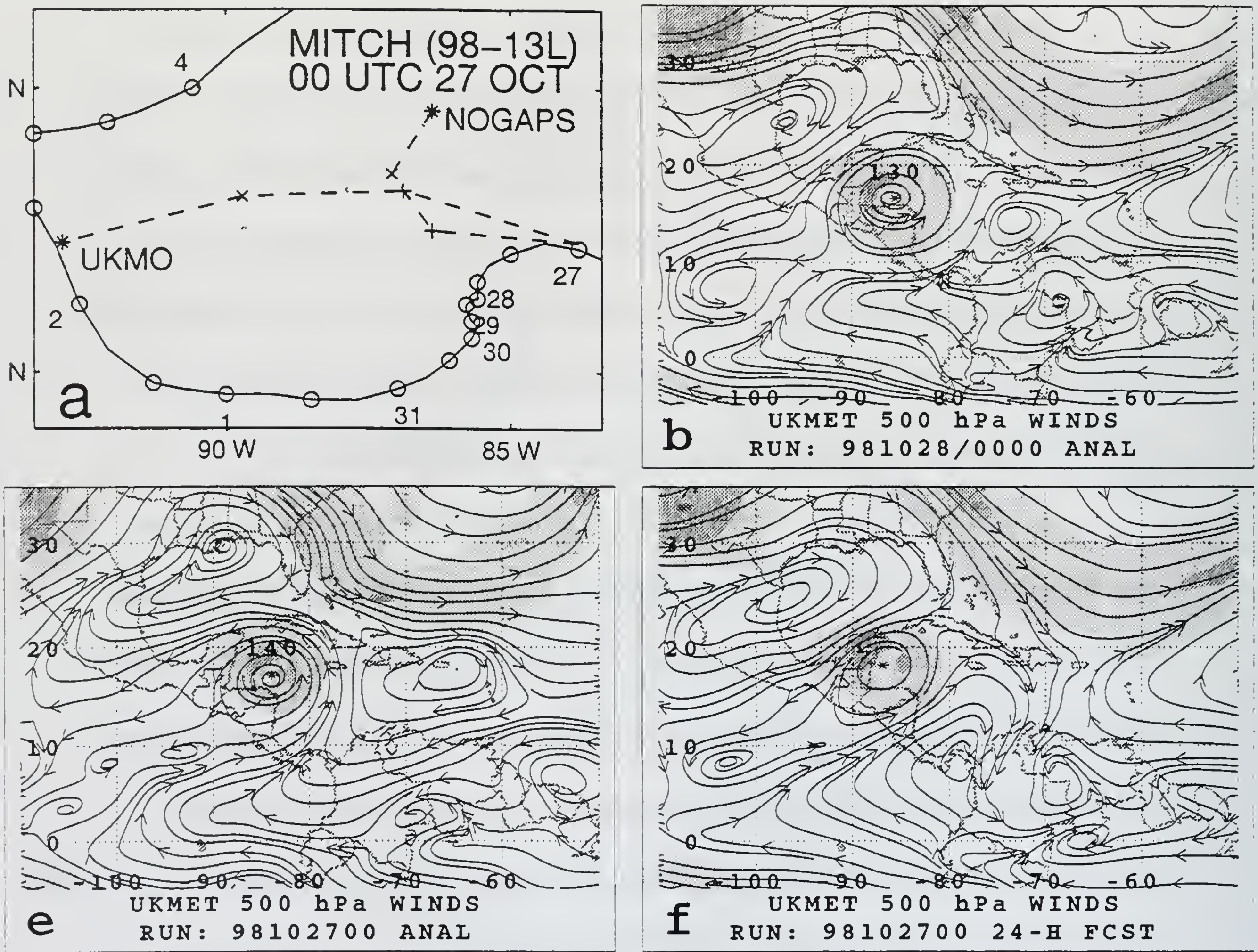

Figure 8. A comparison/verification of the UKMO 500-mb wind forecasts for Mitch initiated at 0000 UTC 27 October 1998. Panels (b)-(d) are the verifying UKMO 500-mb wind analyses, panels (e)-(h) are the 00-, 24-, 48-, and 72-h UKMO forecasts. Isotach shading starts at 20 kt and the increment is 20 kt. The bold numbers above the TC are the intensity (kt).

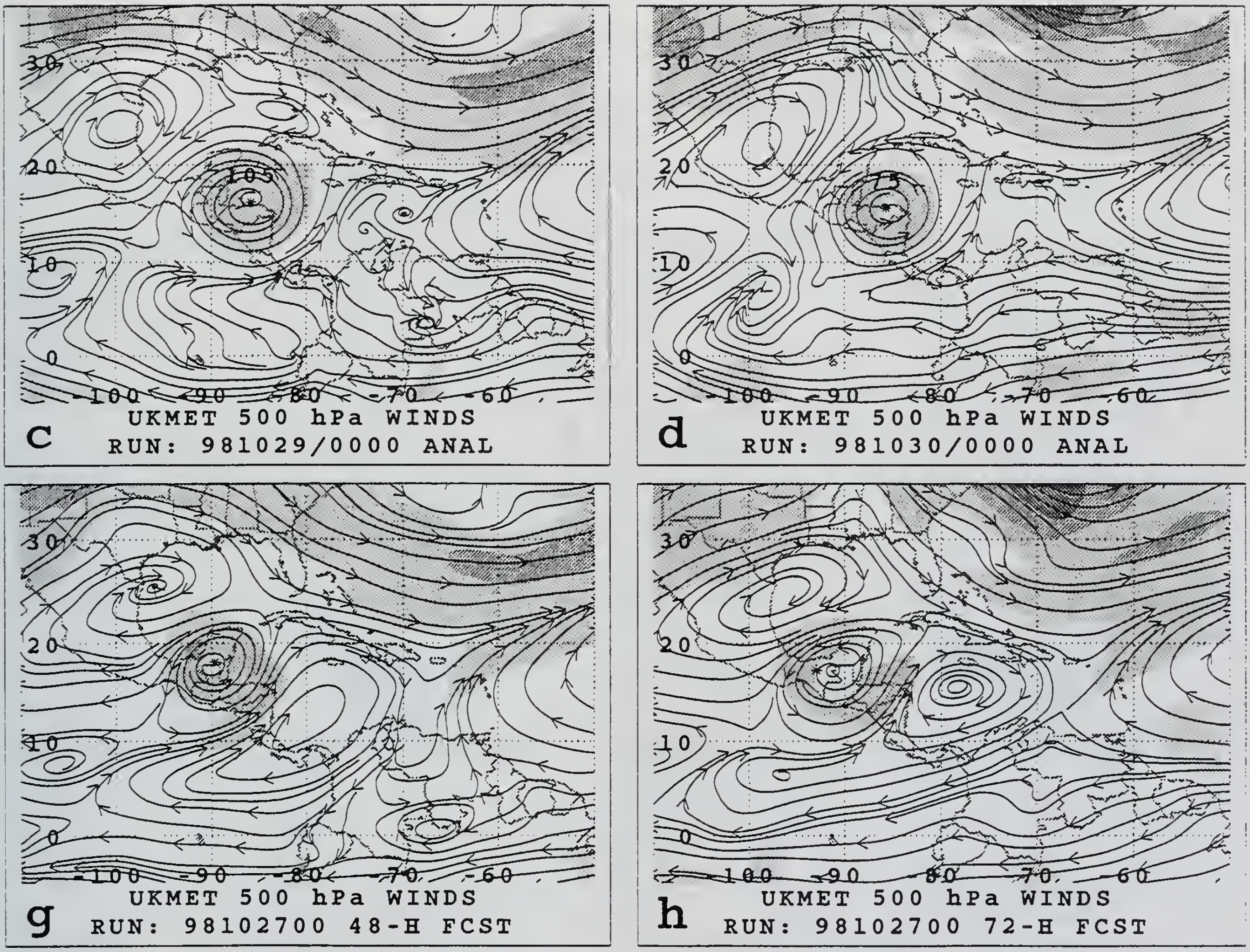

Figure 8. (continued)

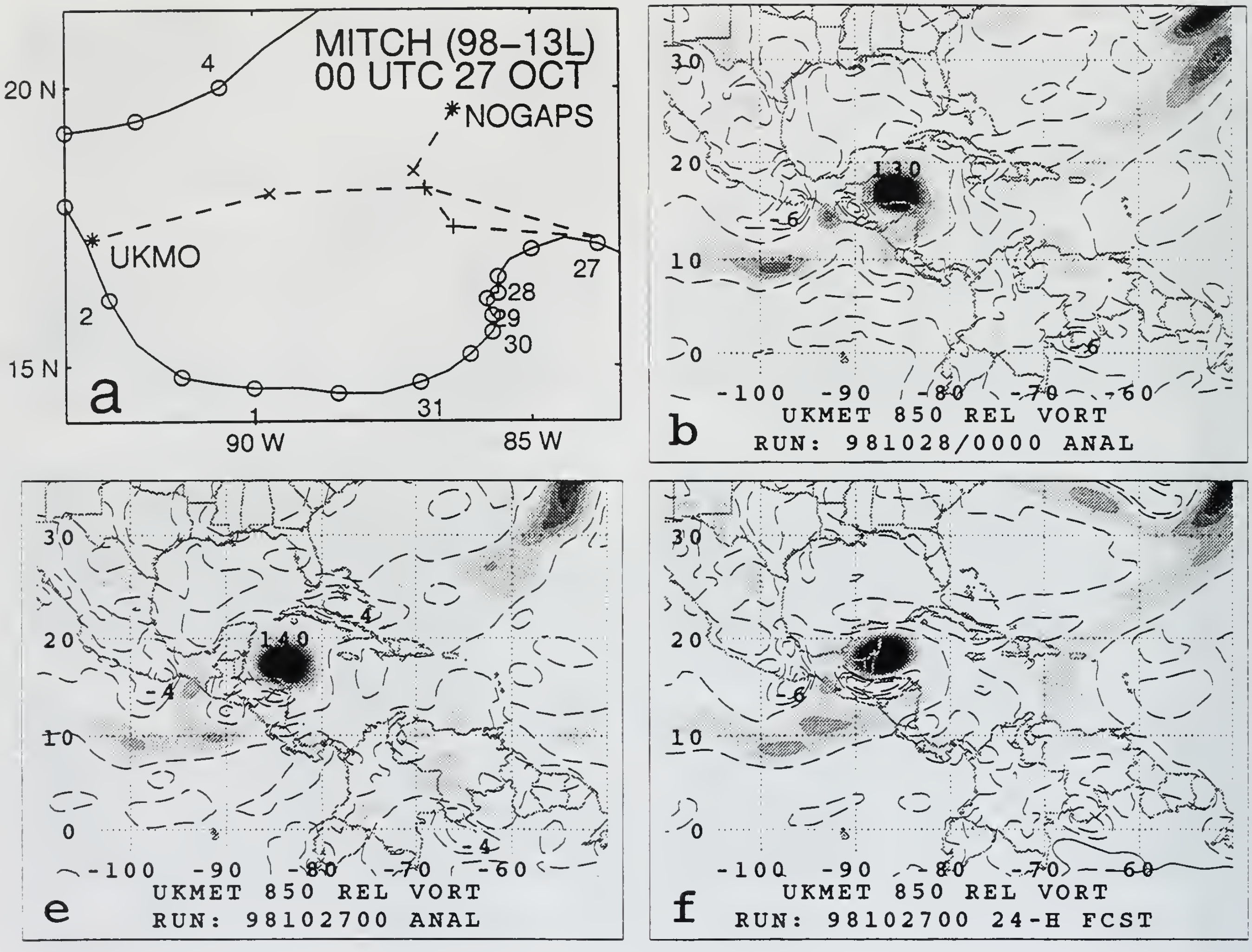

Figure 9. (b-h) As in Fig. 8 b-h, except for 850-mb relative vorticity from the UKMO forecast for Mitch initiated at 0000 UTC 27 October 1998.

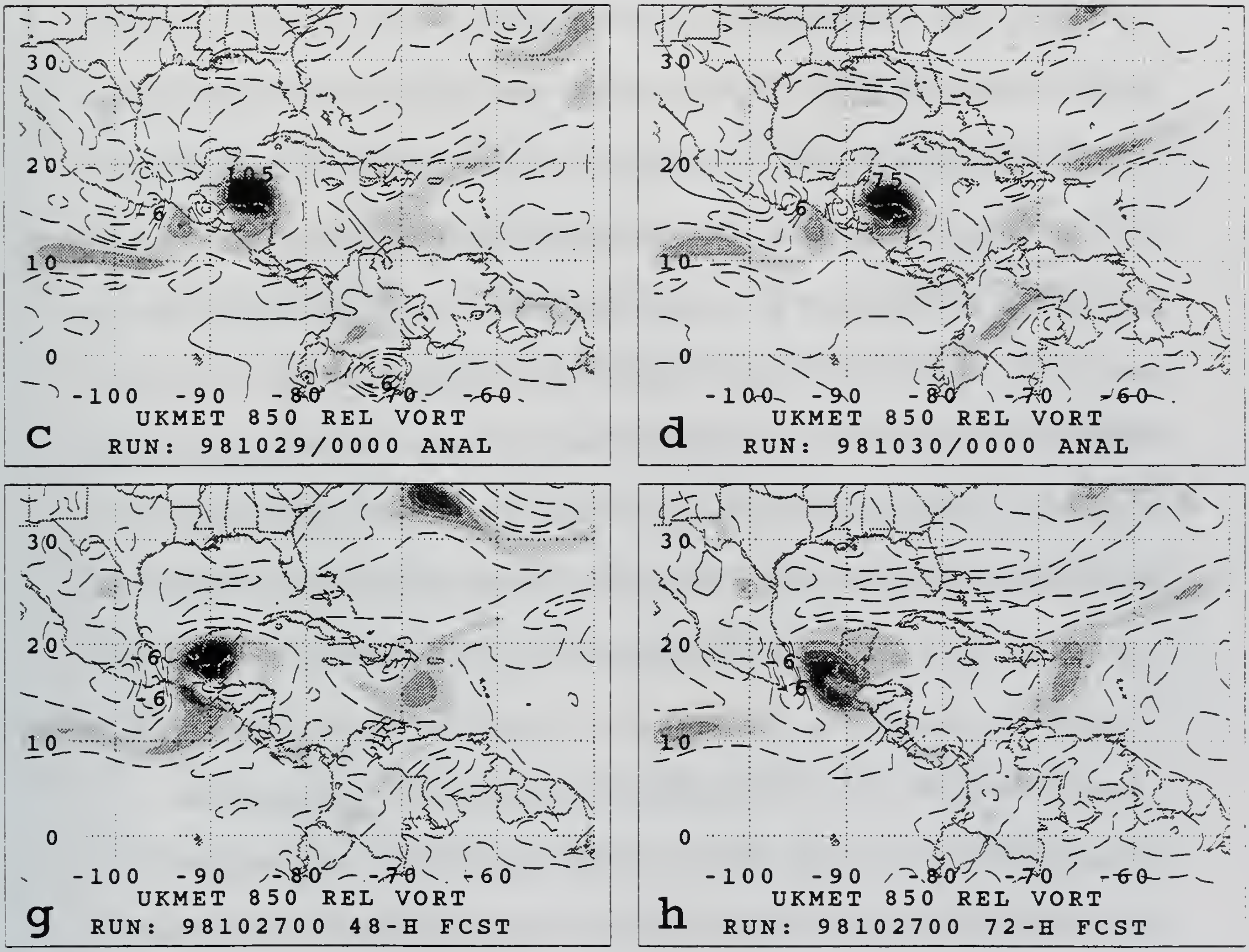

Figure 9. (continued)

A comparison/verification of the NOGAPS sea-level pressure and the UKMO 850-mb relative vorticity fields from the integration initiated at 0000 UTC 28 September is given in Fig. 10 to provide a context for the period of E-DCI. Notice the lower pressure region near 27°N, 53°W to the southwest of the TC at the initial time of 0000 UTC 28 September (Fig. 10e). This low-pressure region is associated with a midlatitude trough that has propagated off the east coast of the U.S. A region of cyclonic relative vorticity near 28°N, 57°W in the UKMO analysis (Fig. 10i) is to the west of the NOGAPS low-pressure region. Even though TC Karl is near 40.3°N, 34.6°W to the north-northeast of TC Jeanne, no interaction between these two TCs is evident. Notice the NOGAPS 24-h forecast (Fig. 10f) has a much weaker TC than in the verifying analysis (Fig. 10b) and the TC track is already west of the best-track (Fig. 10a). The NOGAPS 24-h FTE is 173 n mi, which indicates the possibility of an interaction with the region of low pressure to the southwest as in the E-DCI conceptual model in Fig. 6. Notice that the axis connecting the TC and the low to the southwest in the NOGAPS 24-h forecast (Fig. 10f) is rotated slightly counterclockwise with respect to the axis orientation in the verifying analysis (Fig. 10b), and that the separation of the two cyclones in the 24-h forecast is less than in the verifying analysis. The difference in axis orientation between the 48-h forecast (Fig. 10g) and verifying analysis (Fig. 10c) is even more pronounced, and the forecast separation distance is again too small. In the NOGAPS 72-h forecast (Fig. 10h) the two cyclones are merging, which is manifest by the single elongated area of sub-1008 mb pressures. The orientation of the elongated low-pressure area is shifted cyclonically nearly 90° relative to the verifying analysis (Fig. 10d). This sequence of differences is indicative of E-DCI in NOGAPS. By contrast, the UKMO

model 24- and 48-h forecasts (Fig. 10j and k) predict the region of higher relative vorticity to remain distinct from the TC, and weaken by 72 h. For the same forecast period, the UKMO model predicts an elongated region of cyclonic relative vorticity to move eastward off the east coast of the U.S. and Canada. This region of higher relative vorticity is aligned to the west of the elongated low surface pressure region in the NOGAPS analysis (Fig. 10c). The 72-h UKMO model forecast (Fig. 10l) has two separate regions of cyclonic relative vorticity, with the 850-mb vorticity associated with Danielle near 41°N, 30°W and the second region to the northwest of Danielle. The 24-h time interval makes it difficult to determine where the region of higher relative vorticity originally to the southwest of Danielle has moved. A merger with Danielle, with the region to the northwest of Danielle, or dissipation are possible scenarios.

Recall the conceptual model of DCI in Fig. 6 depicts a counter-clockwise rotation of the axis between the cyclone centers. This case was presented to show a variation of the E-DCI phenomenon in which cyclonic rotation in the forecast fields does not occur because anticyclonic rotation occurs in reality.

d. Summary

A key result for the forecaster is that whereas DCI seems to occur relatively frequently in numerical models (e.g., 16 periods involving six TCs that degraded eight NOGAPS and eight UKMO forecasts from 1997-1998), vigorous track-altering direct interactions between real TCs and other cyclones appear to be rare. The forecaster needs to be aware of the model representation of the TC size/depth and location, and possible interactions of the TC in the first-guess field and synthetic

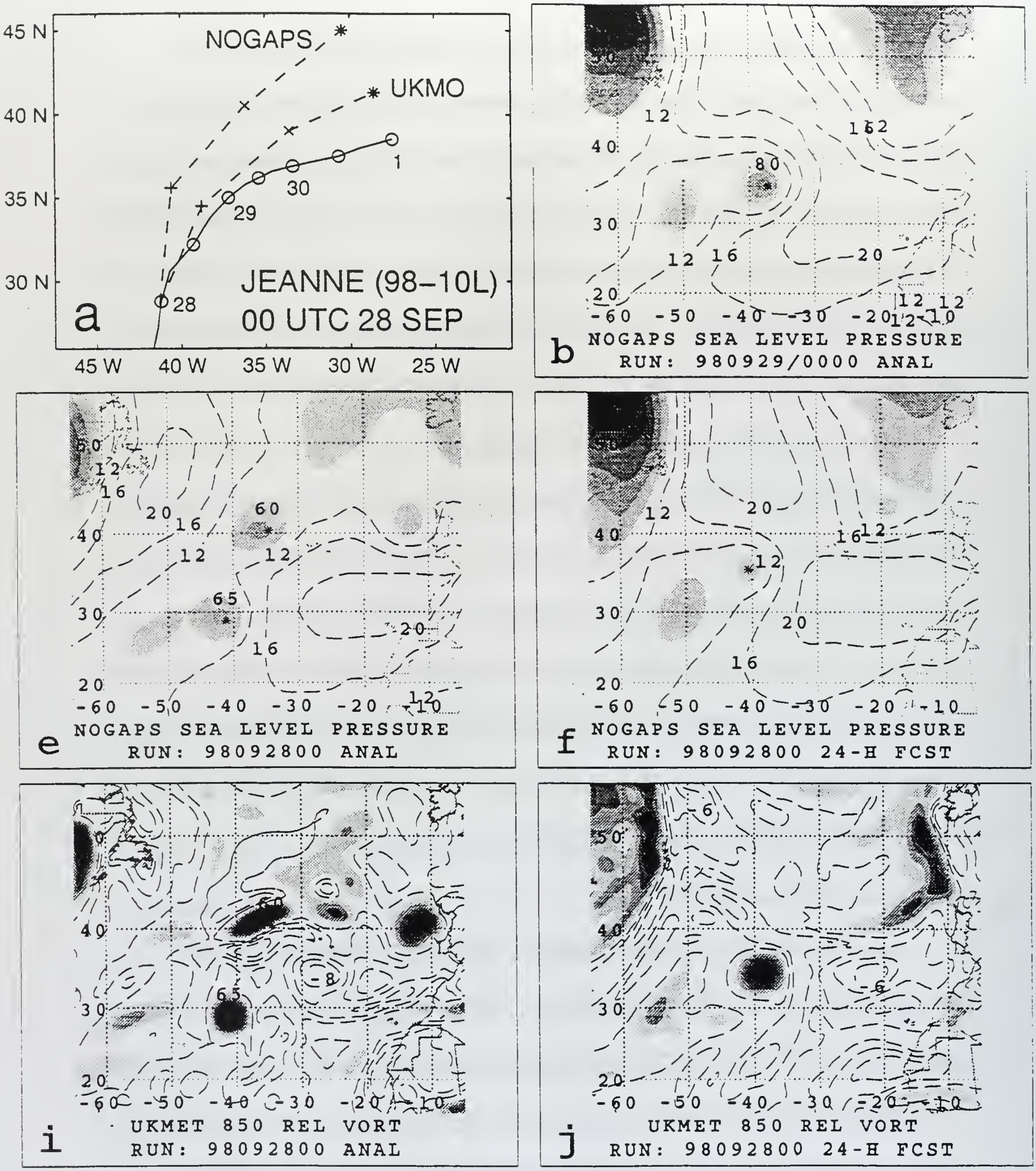

Figure 10. (a) Track of TC Jeanne (98-10L) and forecast tracks by selected models (see inset), with the dynamical models beginning at 0000 UTC 28 September 1998. The 72-h (asterisk) positions are shown for the dynamical models. Panels (b)-(h) as in Fig. 8,

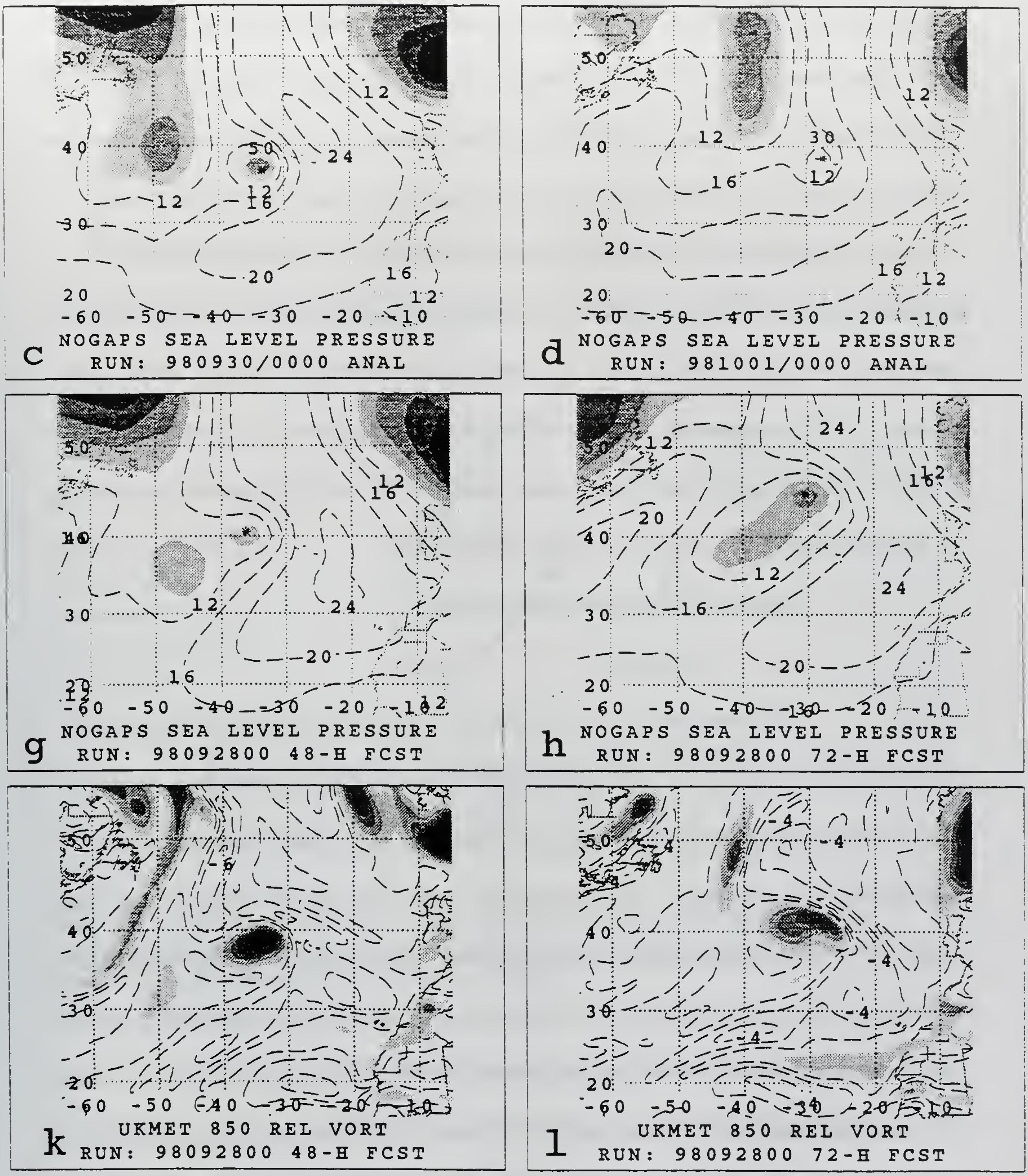

Figure 10. (continued) except for NOGAPS sea-level pressure forecasts for Jeanne initiated at 0000 UTC 28 September 1998. Shading starts for a pressure of 1008 mb and the increment is 4 mb. Panels (i)-(l) as in Fig. 9 (e)-(h), except for the UKMO 850-mb vorticity forecast initiated at 0000 UTC 28 September 1998.

observations of the cyclone. In addition, the second TC must be identified as a real or false disturbance, or another TC (or precursor of a developing TC). The key feature to aid the forecaster in identifying the E-DCI phenomenon is a closed cyclone or streamline trough that rotates cyclonically about the TC in an absolute sense, or relative to an unaffected model, and that may merge with the TC circulation. At the surface, the forecaster should look for a closed low or a trough that rotates cyclonically about and may merge with the TC circulation. As in the western North Pacific study of Carr and Elsberry (1999), and pending any new information to the contrary, the forecaster will normally be justified in treating any model-predicted DCI as E-DCI, and either rejecting or giving low weight to the track forecast of that model.

2. Indirect Cyclone Interaction (ICI)

a. Description

The conceptual model for indirect cyclone interaction on an eastern TC (ICIE) is depicted in Fig. 11. A large TC, disturbance, midlatitude trough, or cutoff low that is well to the northwest of an eastern TC develops a large peripheral anticyclone between the two circulations. The development of the large peripheral anticyclone may be a result of barotropic, Rossby wave dispersion (Carr and Elsberry 1995) or baroclinic influences. Excessive ICIE (E-ICIE) occurs when the dynamical model predicts that the peripheral anticyclone generated by the western cyclone will force the eastern TC to take a more equatorward track than in reality. This may occur if the peripheral anticyclone is too large or if the eastern TC is too small. Insufficient ICIE (I-ICIE) occurs when the numerical model predicts that the peripheral anticyclone generated by the western cyclone will be weaker and steer the eastern TC on a less equatorward track. Again, the

determining factor is the model predicted size of the peripheral anticyclone and/or of the eastern TC.

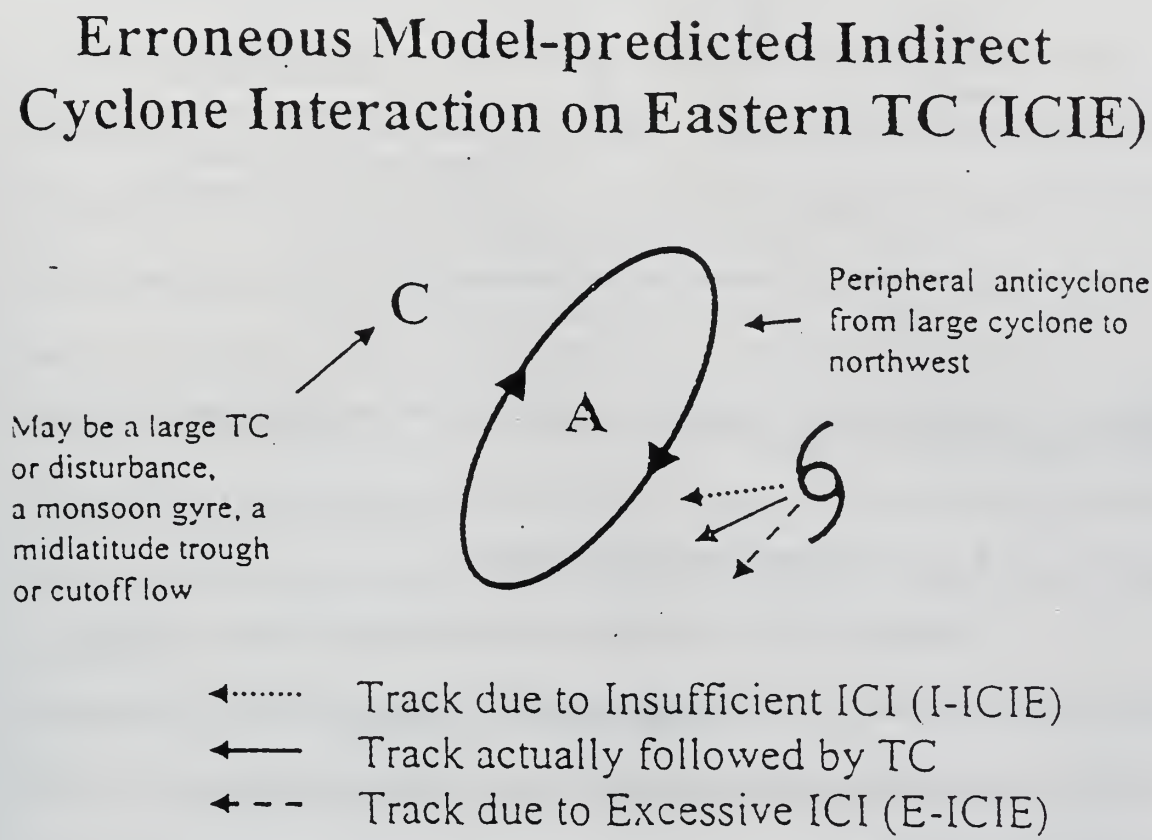

Figure 11. Conceptual model when large forecast track errors are associated with insufficient (dotted arrow) or excessive (dashed arrow) Indirect Cyclone Interaction on Eastern TC (ICIE) [from Carr and Elsberry (1999)].

The conceptual model for indirect cyclone interaction on a western TC (ICIW) is shown in Fig. 12. The key factor in ICIW is the diminished peripheral anticyclone strength associated with the western TC due to the approach of the cyclonic circulation to the east. Insufficient (Excessive) ICIW will result in a more (less) poleward track bias.

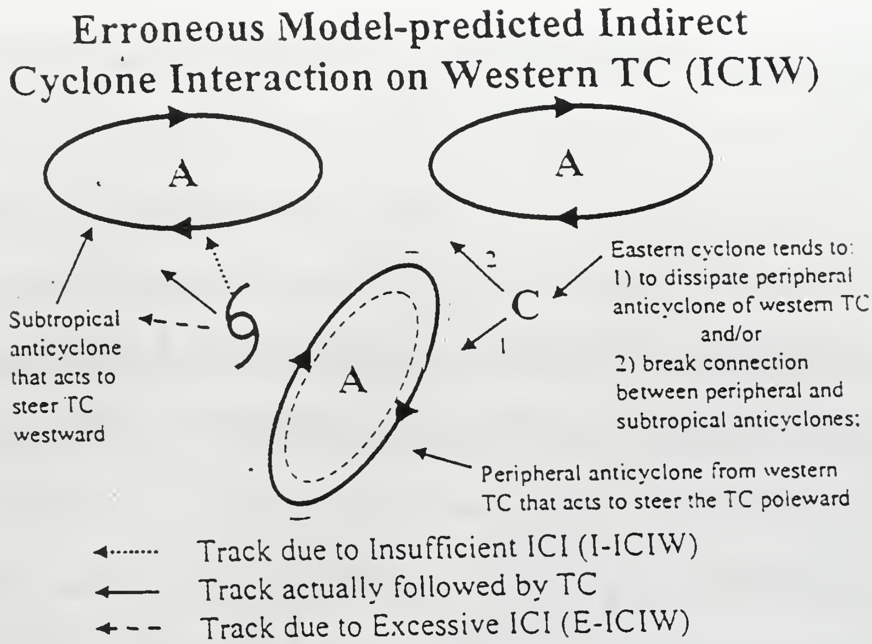

Figure 12. Conceptual model as in Fig. 11, except for erroneous ICI on the western TC [from Carr and Elsberry (1999)].

b. Frequency and Characteristics

During the 1997 and 1998 North Atlantic hurricane seasons, only four forecasts were degraded by ICIE (all were excessive in nature), and none were degraded by ICIW. No case studies are presented here due to the infrequent occurrence of the ICIE or ICIW error mechanisms.

B. BETA EFFECT-RELATED PROCESSES

The error mechanisms in Table 4 that involve the beta effect are Ridge Modification by the TC (RMT), Reverse Trough Formation (RTF), and TC Initial Size (TCS). All of these error mechanisms are associated with the dependence of the beta effect (both propagation and wave train generation) on TC size. Excessive TCS (E-TCS), which may result if a too large TC size is specified, degrades model forecast tracks via the E-RMT mechanism. However, E-TCS did not occur in the Atlantic sample.

1. Ridge Modification by the Tropical Cyclone (RMT)

a. Description

A conceptual model of RMT is provided in Fig. 13. The typical environmental structure associated with RMT is a transition from the S/TE to the P/PF synoptic pattern/region. The key is whether the transition occurs too slowly or rapidly and the resulting steering influences upon the TC. The western North Pacific occurrences of erroneous RMT as studied by Carr and Elsberry (1999) all involved cases when the TC was embedded in a Rossby wave train of a large cyclonic circulation to the west and north (Fig. 14). The cyclonic circulation generates a peripheral anticyclone to the northwest of the affected TC. As the energy propagates southeastward along the wave train, the TC and its peripheral anticyclone may also grow. Excessive (Insufficient) RMT will occur in the dynamical model if the propagation of energy is stronger (weaker) than in reality.

b. Frequency and Characteristics

In the 1997-1998 sample of NOGAPS and UKMO track forecasts, 13 periods (based on model initialization time) involving four hurricanes were identified when RMT occurred sometime during the model integration (Table 6). As previously mentioned, the ECMWF model had no poor forecasts attributed to RMT. The track forecasts of the models were degraded by excessive RMT (E-RMT) in every case except the UKMO forecast for Erica (97-06L) that was initiated at 1200 UTC 5 September, which involved I-RMT. The case study that follows will show that E-RMT is reasonably easy to identify with the proper model fields and an understanding of the clues that identify E-RMT.

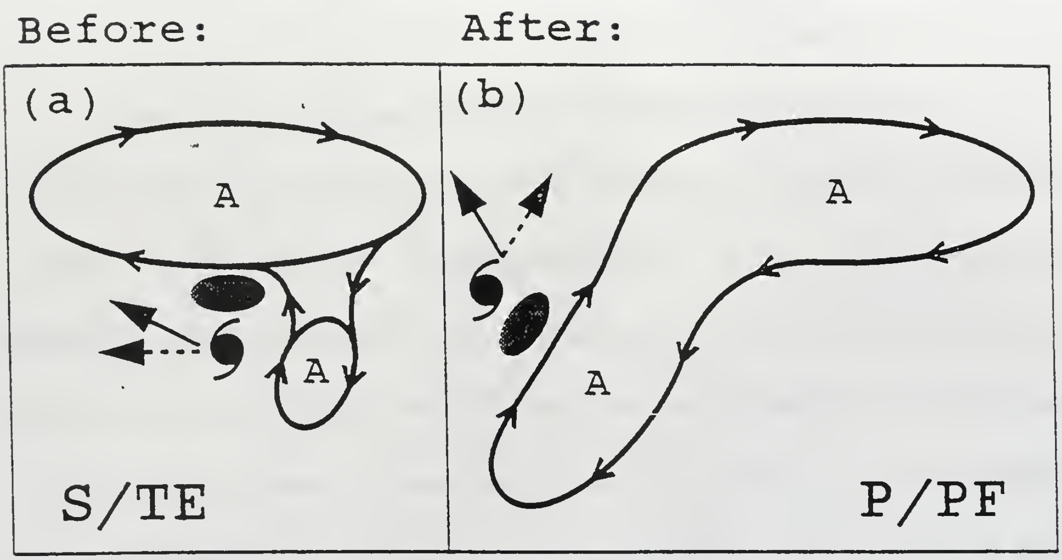

Figure 13. A conceptual model for the Ridge Modification by a TC (RMT) transformation from the (Before) Standard/Tropical Easterlies (S/TE) to the (After) Poleward/Poleward Flow (P/PF) synoptic pattern/region. A smaller (larger) TC will move along the dashed (solid) arrow because of the beta-effect propagation [from Carr and Elsberry (1999)].

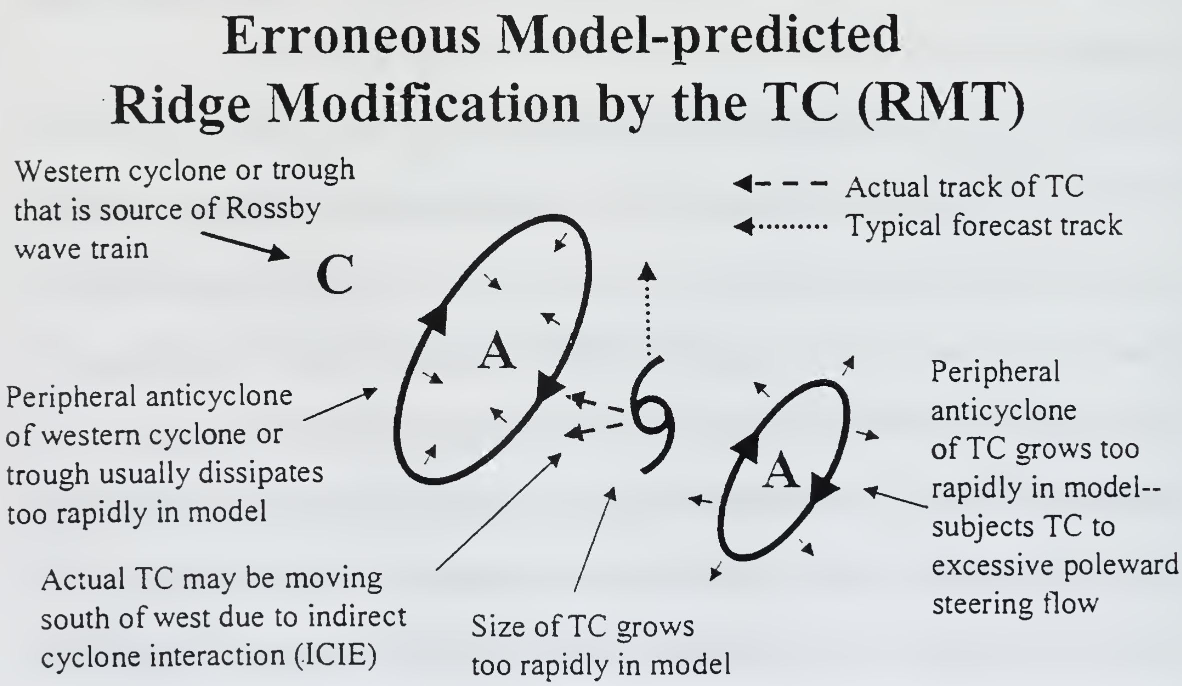

Figure 14. Erroneous RMT as in Fig. 13 influencing the forecast track of a TC embedded in the wave train of another cyclone (C) to the northwest (Northern Hemisphere) [from Carr and Elsberry (1999)].

Table 6. Cases of erroneous model-predicted Ridge Modification by the TC (RMT) in the North Atlantic during the 1997 and 1998 hurricane seasons. See Table 5 for explanatory footnotes.

TC No	Starting times of affected model runs[1]	Synoptic Environment of affected TC	Degree Of RMT	Models affected[5]
97-06L	Sep 5/12	P/PF → M/MW	Insufficient	U
98-02L	Aug 20/12	S/TE	Excessive	U
98-04L	Aug 26/12- 29/12	S/TE → P/PF	Excessive	U
98-13L	Oct 27/12- 30/12	P/PF → S/EF	Excessive	N

c. *Case Study of Hurricane Mitch (98-13L)*

For this hurricane, the NOGAPS track forecasts were affected by E-RMT for seven model integrations beginning at 1200 UTC 27 October and continuing through 1200 UTC 30 October (Table 6). At the model integration time of 1200 UTC 27 October, Hurricane Mitch is near 17.1°N, 85.0°W with an intensity of 145 kt. The TC is translating toward 247° at 5 kt (Fig. 15a) and is in the S/EF synoptic pattern/region and will transition to the S/TE synoptic pattern/region by the end of the forecast period. For this case study, the forecast position was manually extracted from the predicted fields because the NOGAPS tracker lost the vortex prior to 72 h. The NOGAPS forecast track is far north of the best-track position with a 72-h FTE of approximately 420 n mi. Whereas the TC slowly moved to the west and then southwest, the NOGAPS model forecast track was northwestward for 48 h and then poleward.

A comparison/verification of the NOGAPS 500-mb wind (sea-level pressure) fields from the integration initiated at 1200 UTC 27 October is given in Fig. 15 (16) to provide a context for the period of E-RMT. In the initial analysis of NOGAPS

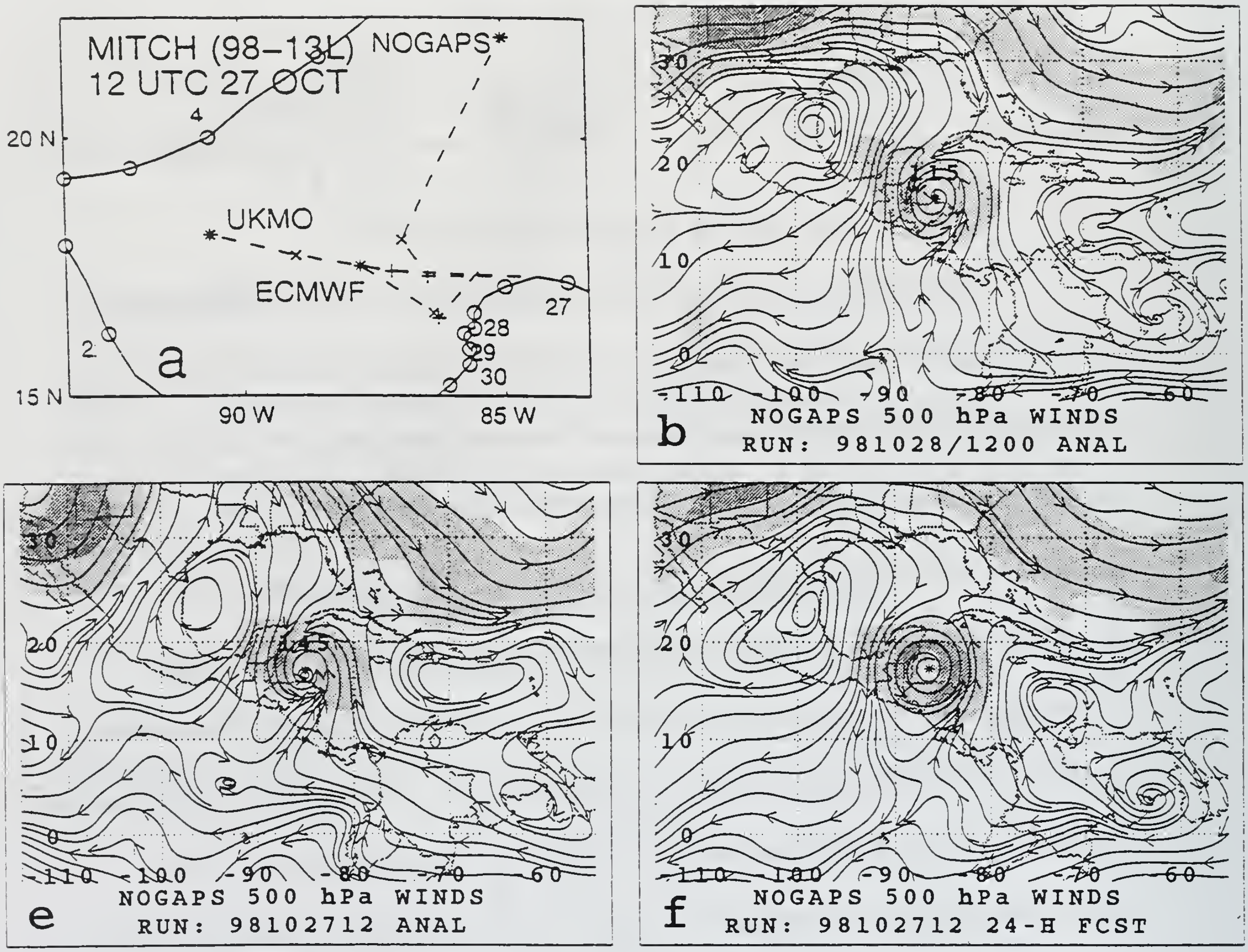

Figure 15. As in Fig. 8, except for NOGAPS 500-mb wind field forecasts for Mitch initiated at 1200 UTC 27 October 1998.

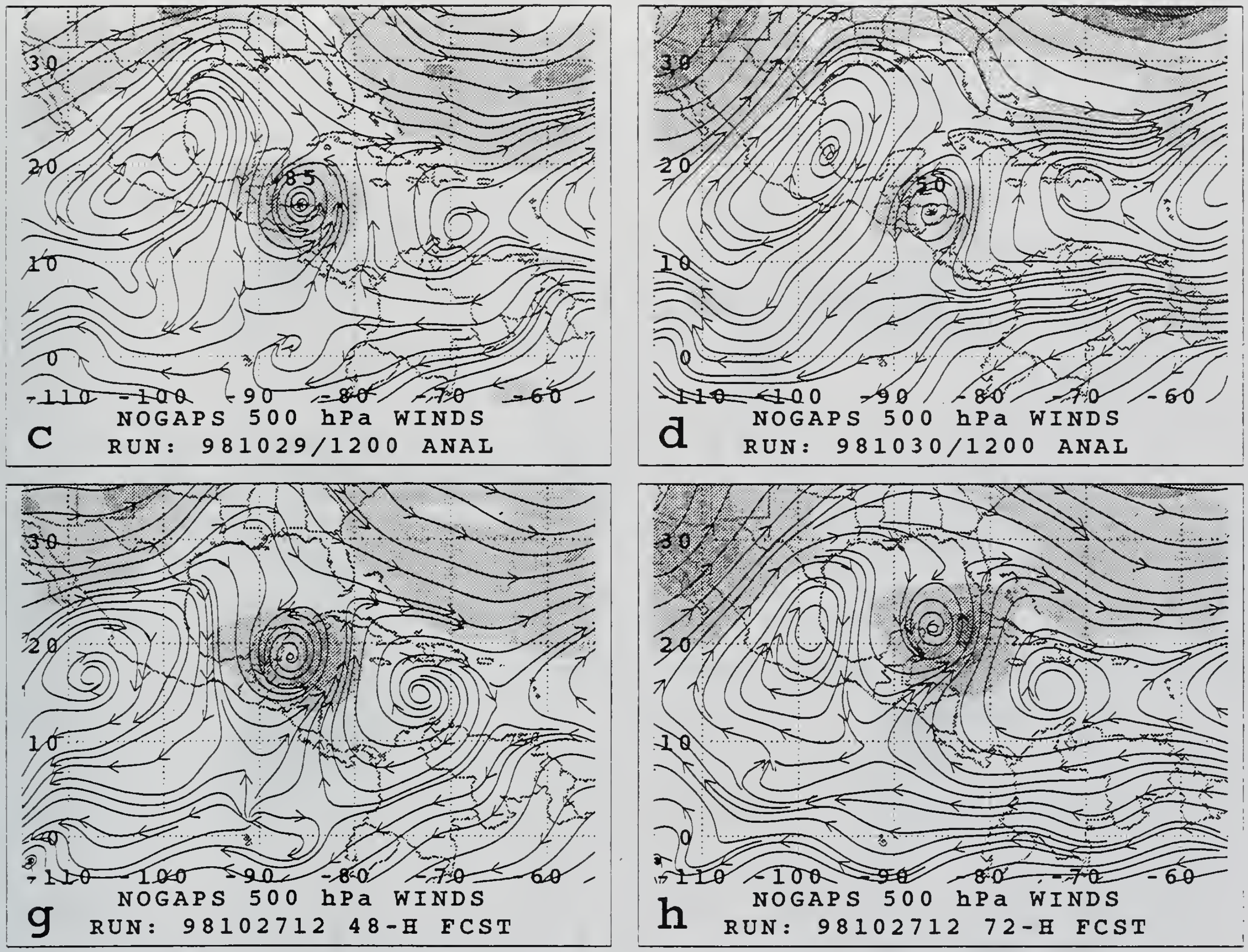

Figure 15. (continued)

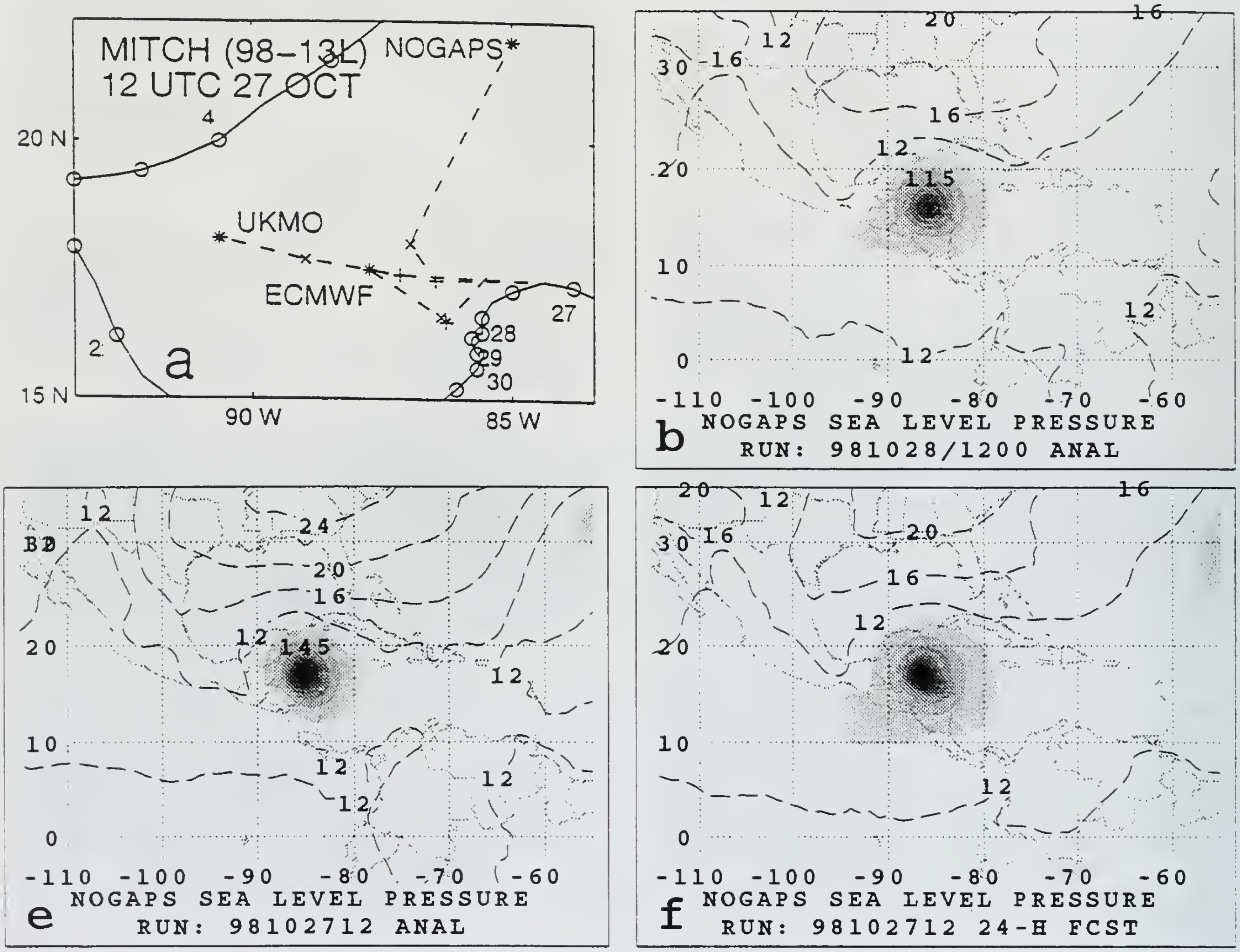

Figure 16. As in Fig. 15, except for NOGAPS sea-level pressure forecasts for Mitch initiated at 1200 UTC 27 October 1998.

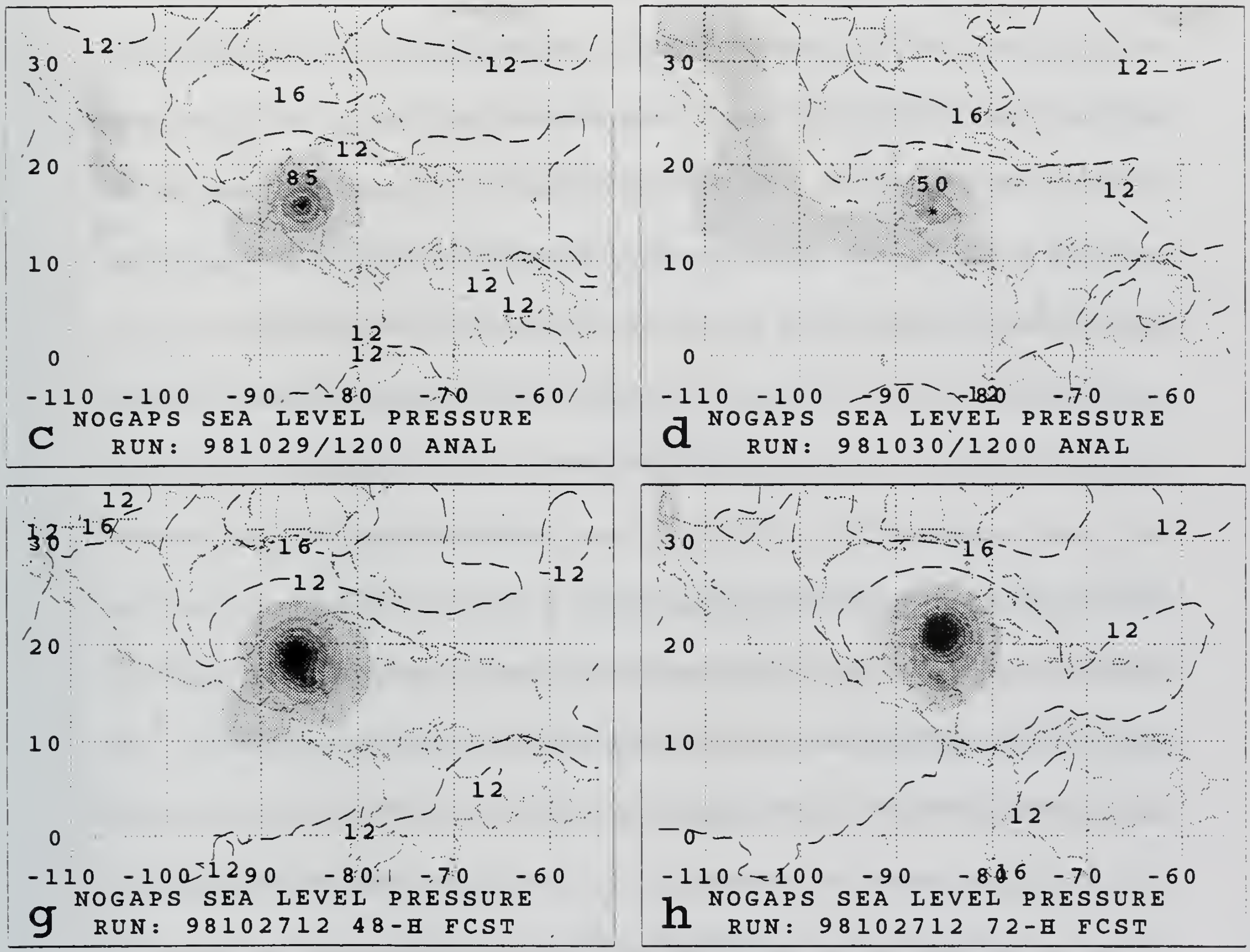

Figure 16. (continued)

(Fig. 15e), the circulation of Mitch was in a northwest-to-southeast Rossby wave train starting with a high-amplitude midlatitude trough over the western United States, a large peripheral anticyclone over the western Gulf of Mexico, Mitch, and the peripheral anticyclone of Mitch over the central Caribbean. During the NOGAPS integration (Fig. 15 f-h), the circulation around Mitch intensifies, as noted by the isotach maximum wrapping around the TC from the southern side counter-clockwise to the northwest periphery. By 72 h (Fig. 15h), the isotach maximum is east of the TC, which is indicative of a northward steering flow. The NOGAPS forecast of the western U.S. trough and the associated peripheral anticyclone to the northwest of Mitch is in fairly good agreement with the verifying analyses (Fig. 15 b-d). However, the NOGAPS forecast of the peripheral anticyclone to the southeast of Mitch is much stronger at 48 h and 72 h (Fig. 15g and h) than in the verifying analyses (Fig. 15c and d). In addition, the NOGAPS sea-level pressure forecasts (Fig. 16 f-h) have a much deeper and larger horizontal extent of Mitch compared to the verifying analysis (Fig. 16 b-d). This predicted growth provides the forecaster an indication that the model is propagating too much Rossby wave train energy and strengthening the TC and its peripheral anticyclone too much. The subsequent two NOGAPS model integrations initiated at 0000 UTC 28 October and 1200 UTC 28 October (not shown) continue this trend of overforecasting the strength of the TC and its peripheral anticyclone, which provides a clear and persistent indication of E-RMT.

d. Summary

A key task for the forecaster is to identify the large-scale features in the environmental structure. For storms in the Atlantic basin or Gulf of Mexico, the

forecaster needs to be aware of conditions far westward to identify any high-amplitude troughing or vigorous cut-off lows. Excessive growth in the TC and its peripheral anticyclone due to the influence of a Rossby wave train from cyclones to the west and north (compared to unaffected models) are the key indicators. In examining the streamline fields, the forecaster needs to look for rapid amplification of the peripheral anticyclone to the southeast of the affected TC and dissipation of the anticyclone to the northwest of the TC. As in the case study above (Fig. 15 f-h), the isotach maximum will rotate from the northern quadrant to the eastern quadrant. The forecaster may also note rapid growth of the TC surface circulation. The dynamical model tracks will depict a poleward track change as the peripheral anticyclone of the TC amplifies and becomes the primary steering flow during E-RMT.

2. Reverse Trough Formation (RTF)

a. Description

The Reverse Trough Formation (RTF) conceptual model is shown in Fig. 17. Two initially east-west oriented TCs become aligned along a southwest-to-northeast axis. As the peripheral anticyclones of these two TCs merge, an extensive anticyclone with a southwest-to-northeast axis then develops to the east so that both TCs turn to a more poleward track.

b. Frequency and Characteristics

In the 1997-1998 sample of the NOGAPS, UKMO, and ECMWF track forecasts, only one model initialization time was identified when RTF occurred sometime during the model integration (Table 4). This is in contrast to the western North Pacific studies of Carr and Elsberry (1999) in which 10 NOGAPS and two GFDN forecasts were

degraded by erroneous RTF. In the Atlantic, the only occurrence of a track forecast degraded by RTF was for the UKMO model during Hurricane Mitch. Since this error mechanism is so rare, a case study is not included.

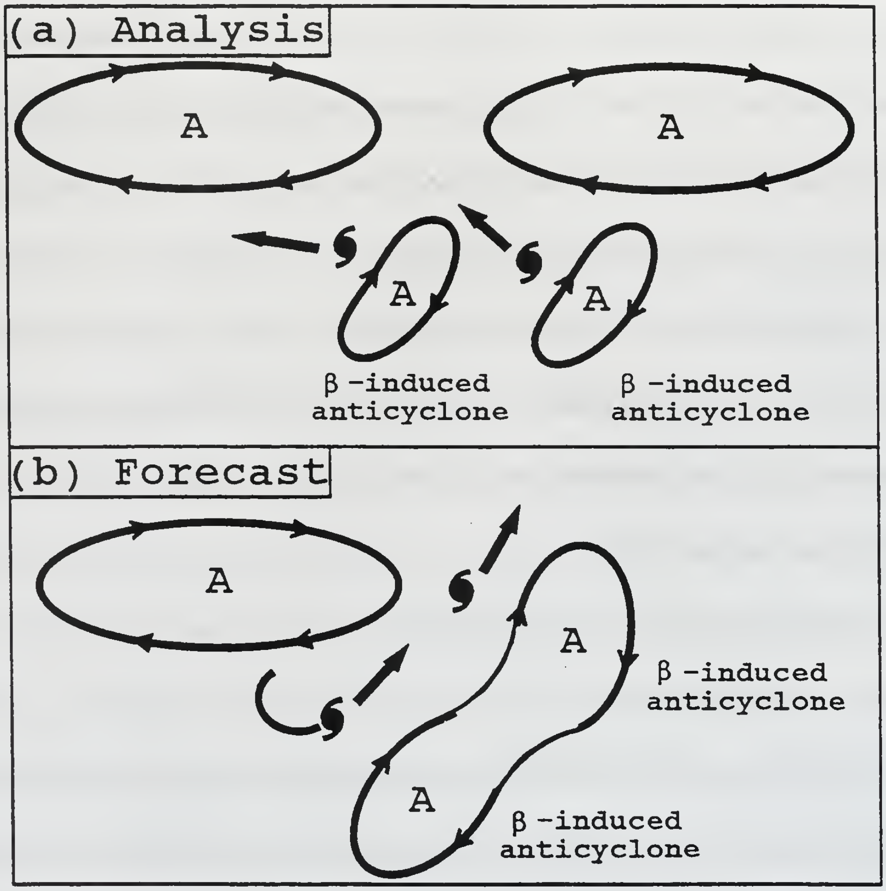

Figure 17. Conceptual model as in Fig.13, except for a Reverse Trough Formation (RTF).

3. Tropical Cyclone initial Size (TCS)

a. Description

In the Systematic Approach, the size of the TC is defined based on the expected beta-effect propagation (BEP) speed (Carr et al. 1997). Erroneous TCS actually degrades the model forecast via the RMT error mechanism. However, that occurs with

an erroneous initial specification or forecast of the TC size. Erroneous TCS must be treated separately whenever the TC size in the initial analysis is in error. The model ability to properly represent the TC size is partially dependent upon the horizontal resolution of the model. Recall that the NOGAPS, UKMO, and ECMWF models have horizontal resolutions of ~ 75, 60, and 40 km, respectively. In addition, all three models use different initialization methods in defining the TC prior to the model integration. Different physical representations (especially convective latent heat release) may also lead to an erroneous TC size.

b. Frequency and Characteristics

In the 1997-1998 sample of the NOGAPS, UKMO, and ECMWF track forecasts, five periods (based on model initialization time) were identified when TCS occurred sometime during the model integration (Table 4). Three of these five forecasts were associated with Hurricane Mitch after landfall in Central America and a then re-emergence offshore. Both the NOGAPS and UKMO models had forecast track errors degraded by insufficient TCS (I-TCS). In the western North Pacific studies of Carr and Elsberry (1999) the only TC degraded by TCS was for the small Typhoon Paka. Even though 14 forecasts (nine for GFDN and five for NOGAPS) for Typhoon Paka were degraded by E-TCS, this was essentially for the same reason. Since the TCS error mechanism is relatively rare in the Atlantic, no case study is presented here.

C. MIDLATITUDE-RELATED PROCESSES

The error mechanisms in Table 4 that involve midlatitude-related processes are Response to Vertical wind Shear (RVS), Baroclinic Cyclone Interaction (BCI), and Midlatitude System Evolutions (MSE). All processes for which TC interaction with the

environment is an inherent factor (i.e., each of the above error mechanisms except MSE) are grouped together in Table 4. In this section, RVS will be addressed first, followed by BCI and MSE.

1. Response To Vertical Wind Shear (RVS)

a. Description

A conceptual model of erroneous RVS is given in Fig. 18. The keys to RVS are the differences between the actual and model-depicted vertical structure and the amount of tilt of the TC. The vertical structure differences are that an intense (deep) TC will follow the average environmental steering over a greater depth of the troposphere, whereas a weak (shallow) TC will have an environmental steering in the lower troposphere. Differences in the actual versus the model-predicted vertical structures will lead to FTE due to an erroneous translation speed in the model. In the Atlantic, strong vertical wind shear will normally be encountered as the TC moves poleward of the subtropical ridge axis and approaches the midlatitude westerlies. An important clue for RVS (Carr and Elsberry 1999) is a vertical decoupling of the 500-mb and sea-level pressure circulations. The RVS error mechanism may be categorized as either Insufficient (I-RVS) or Excessive (E-RVS) with a fast-track or slow-track bias, respectively.

b. Frequency and Characteristics

In the 1997-1998 sample of NOGAPS, UKMO, and ECMWF track forecasts, seven forecasts (based on model initialization time) involving four hurricanes were identified when E-RVS occurred sometime during the model integration (Table 7).

None of the cases involved I-RVS. No cases of RVS affecting the ECMWF forecasts were found.

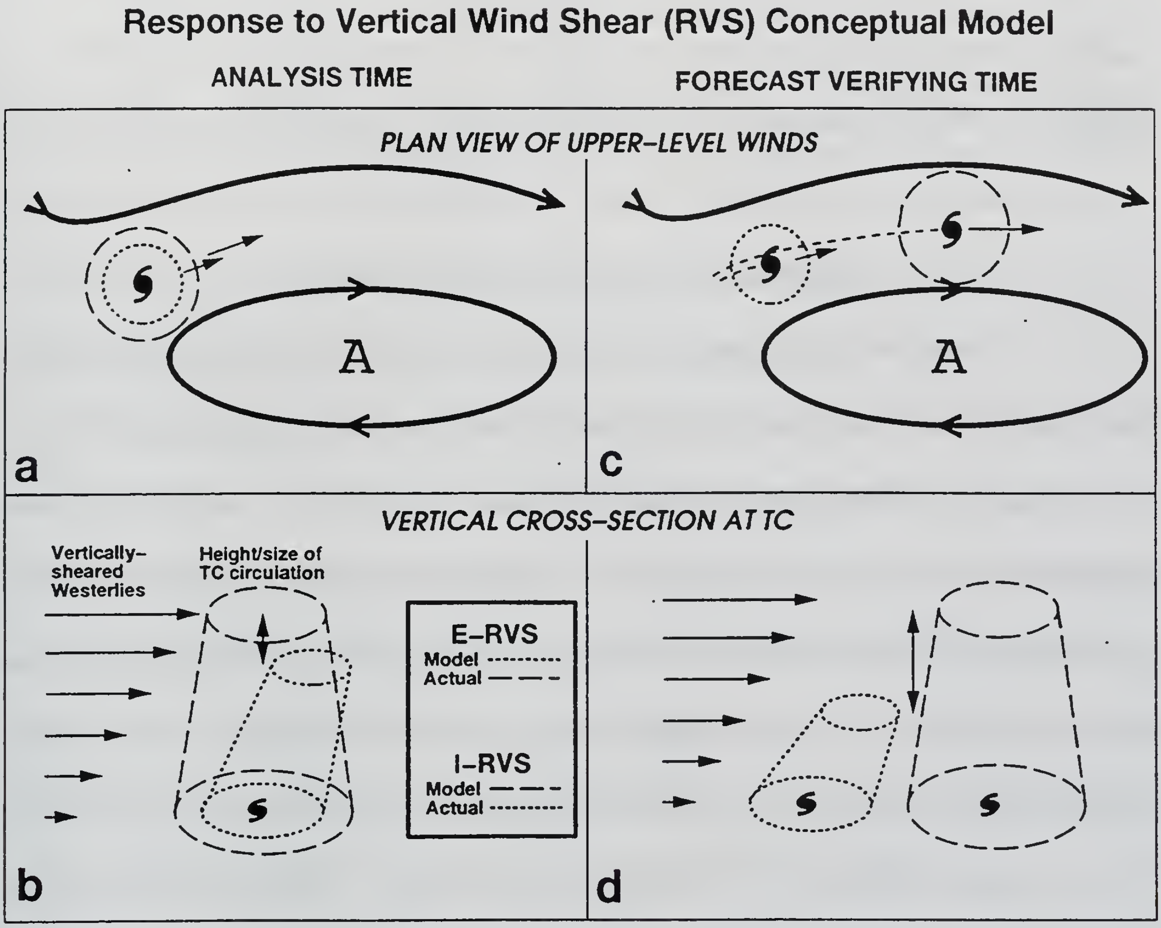

Figure 18. A conceptual model of Response to Vertical Wind Shear (RVS) of a TC in a dynamical model. (a) Plan view of the 500-mb environmental flow and (b) vertical cross-section along the vertical wind shear vector through the TC with different vertical (and presumably horizontal) extents in the model and in nature at analysis time. (c)-(d) Corresponding plan view and vertical cross-section at verification time in which excessive RVS (E-RVS) causes the vortex to be too shallow (panel d, dotted) and the track to have a slow bias (panel c, dotted). Insufficient RVS (I-RVS) leads to a vortex that is too deep and a fast track bias (dotted lines in panels c and d) [from Carr and Elsberry (1999)].

Table 7. Cases of erroneous Response to Vertical wind Shear (RVS) in the North Atlantic during the 1997 and 1998 hurricane seasons. See Table 5 for explanatory footnotes.

TC No	Starting times of Affected model runs	Initial synoptic Environment of affected TC	Character of Response to Vertical Shear	Models Affected[5]
97-01L	Jul 01/00	M/MW	Excessive	N
98-02L	Aug 27/00-27/12	S/PF → M/PF	Excessive	U
98-02L	Aug 27/12	M/PF	Excessive	N
98-04L	Aug 31/00	P/PF	Excessive	N
98-07L	Sep 15/12	S/TE	Excessive	U
98-07L	Sep 16/00	S/TE	Excessive	N

c. *Case Study of Hurricane Danielle (98-04L)*

The NOGAPS forecast for Hurricane Danielle (98-04L) provides a classic case in which E-RVS was clearly evident in the model-predicted fields and track. For this hurricane, the NOGAPS track forecasts initiated at 0000 UTC 31 August 1998 were affected by E-RVS (Table 7). At 0000 UTC 31 August, Danielle is near 27.9°N, 74.1°W and is translating toward 342° at 7 kt (Fig. 19a). The TC is in the P/PF pattern/region and will have a transition to the M/PF pattern/region during the forecast period. During this period, Danielle re-strengthens for a short period and the translation speed increases from 6 to 30 kt within 72 hours. The NOGAPS forecast track (Fig. 19a) appears to predict the recurvature location fairly well, but is slow with a 72-h FTE of 347 n mi. By comparison, the UKMO and GFDL track forecasts are only slightly left (poleward) and right (equatorward) of best-track, respectively, with their 72-h FTEs of 135 and 91 n mi, respectively. The question is then why the NOGAPS 72-h track forecast lags far behind the verifying best-track position as well as the other dynamical model track forecasts.

A comparison/verification of the NOGAPS and UKMO 500-mb wind fields from integrations initiated at 0000 UTC 31 August is given in Fig. 19 to provide a

context for the period of E-RVS. In the initial analysis (Fig. 19e), Danielle is just south of the subtropical anticyclone axis. A closed cyclone near Hudson Bay has an associated trough that extends southward to the Ohio River Valley. By 0000 UTC 1 September (Fig. 19b), the long-wave trough has propagated off the east coast of the U.S. and Canada. The westward extension of the subtropical anticyclone cell to the east of the Danielle is becoming more circular. By 0000 UTC 2 September (Fig. 19c), a stronger isotach maximum is to the southeast of Danielle. At this time, Danielle has moved poleward of the subtropical anticyclone axis and is in the southwesterlies of the M/PF pattern/region. Notice that Danielle is analyzed to have a closed circulation and the 1000-mb circulation center (indicated by the asterisk) is nearly vertically aligned with the mid-tropospheric circulation center. By 0000 UTC 3 September (Fig. 19d), the TC translation speed has increased to about 16 kt and the intensity has increased to 85 kt. A much stronger isotach maximum is now located to the southeast of the TC, which is consistent with the rapid translation to the northeast in Fig. 19a. A displacement of the mid-tropospheric circulation to the northwest of the low-level circulation (asterisk) is now evident, but is due to rapid movement of the TC to the northeast.

The NOGAPS 24-h forecast (Fig. 19f) is in very good agreement with the verifying analysis, and the 24-h FTE is only 29 n mi. By 48 h (Fig. 19g), the NOGAPS 500-mb wind field has the TC as a weak trough, rather than a closed circulation as in the analysis (Fig. 19c). More importantly, the trough axis is predicted to be slightly east of the 1000-mb wind center (indicated by the asterisk). At this time, the 48-h FTE is 132 n mi. The 72-h NOGAPS forecast field (Fig. 19h) has no distinct 500-mb trough above the 1000-mb wind center. Recall that the 72-h FTE was 347 n mi with a slow track bias (Fig.

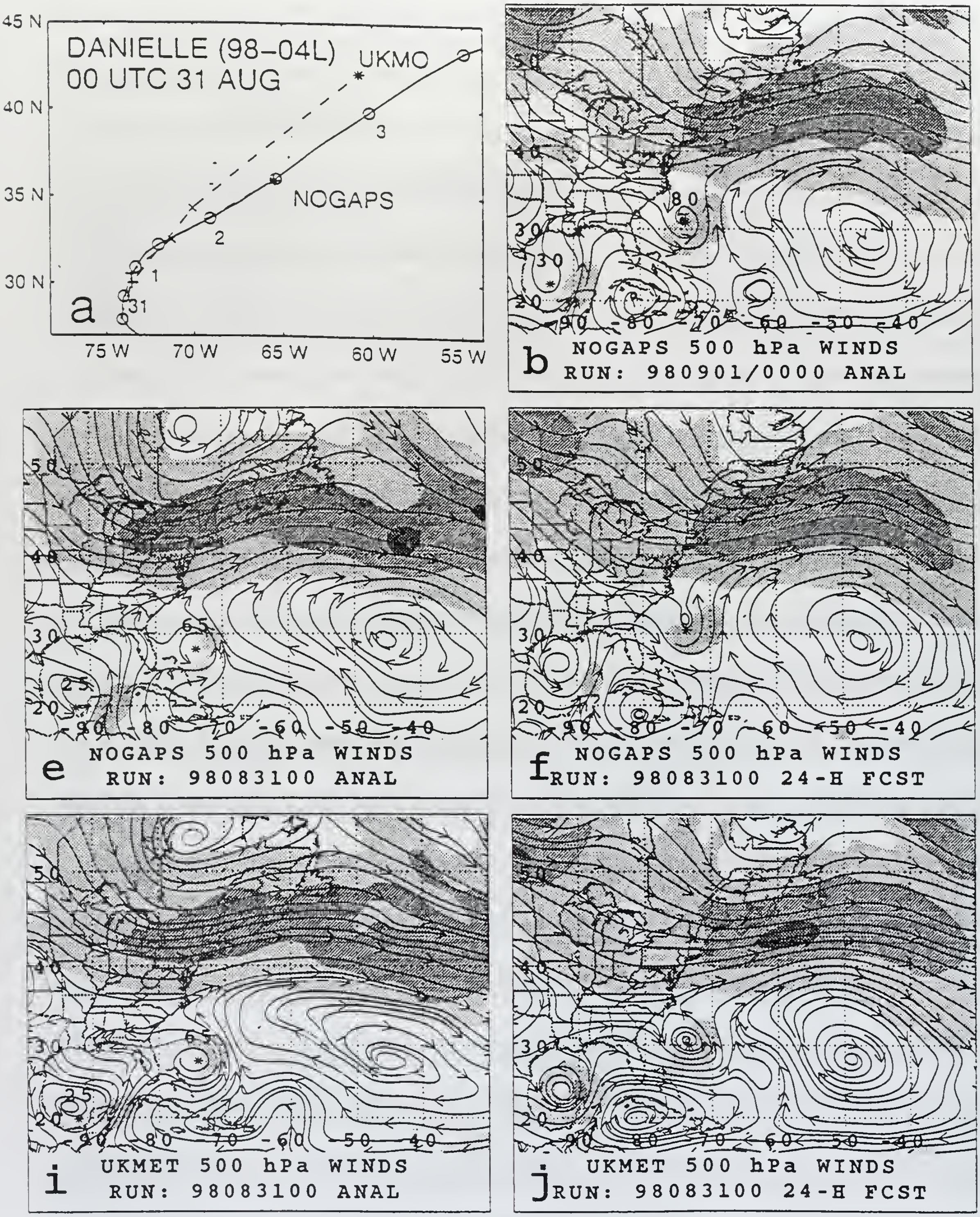

Figure 19. As in Fig. 8, except for NOGAPS and UKMO 500-mb wind forecasts for Danielle initiated at 0000 UTC 31 August 1998.

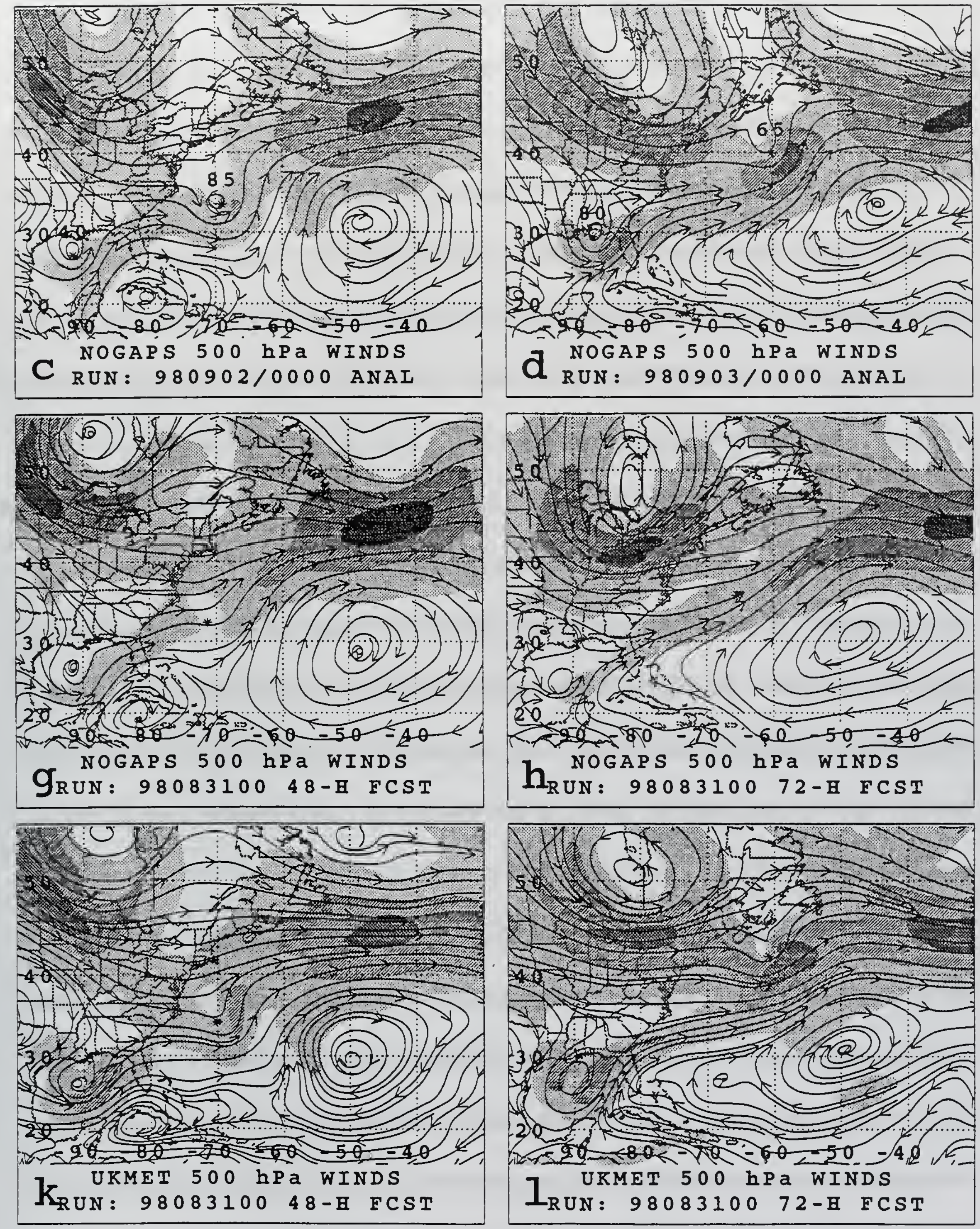

Figure 19. (continued)

19a). An erroneous vertical decoupling of the mid-tropospheric and low-level circulations can lead to a slow track bias as in the conceptual model (Fig. 18). The previous NOGAPS forecast track (not shown) was slightly left of best-track with a 72-h FTE of only 92 n mi. Although the 72-h forecast fields for that integration had indicated a slightly weaker circulation at 500 mb, the key is that the vertical alignment of the 500-mb trough and SLP center was not indicative of E-RVS. The forecast-to-forecast consistency or inconsistency may serve as an alert to the forecaster to search for causes or explanations on which to judge track accuracy.

In the UKMO 500-mb wind forecasts (Fig. 19 j-l), the Danielle SLP center (asterisk) remains more nearly vertically aligned with the 500-mb TC circulation throughout the 72-h period, and the strength of the TC circulation is stronger than in the NOGAPS forecasts. The UKMO model accurately forecasts a weakening of the mid-tropospheric circulation as the closed center weakens to a trough, which is an indication that the model is accurately representing the vertically aligned structure even in this vertically sheared environment.

The corresponding NOGAPS sea-level pressure fields for the forecast initiated at 0000 UTC 31 August are provided in Fig. 20. Notice that the minimum sea-level pressure in the NOGAPS 24-h pressure field (Fig. 20f) is approximately 4 mb higher than in the verifying analysis (Fig. 20b). This trend of a too high minimum sea-level pressure continues at 48 h when the pressure difference was approximately 8 mb (Fig. 20g versus 20c) and at 72 h when the pressure difference increases to approximately 12-16 mb (Fig. 20h and 20d). This trend is consistent with the absence of a cyclonic circulation at 72 h in the NOGAPS 500-mb wind field forecast (Fig. 19d). By contrast,

the UKMO 850-mb relative vorticity forecast fields (Fig. 20 j-l) show no such weakening. At 24 h (Fig. 20j), the UKMO model predicts a nearly circular pattern in the vorticity center near 20°N, 73°W with about the same strength as in the UKMO analysis valid 24 h earlier (Fig. 20i). By 48 h (Fig. 20k), the UKMO model predicts a slight elongation in the vorticity pattern, but still has about the same strength. At 72 h (Fig. 20l), the UKMO model predicts a more dramatic northeast-to-southwest elongation in the vorticity field centered near 42°N, 60°W. This vorticity center is nearly vertically aligned with the UKMO 500-mb trough (Fig. 19l) and low-level circulation center (asterisk, Fig. 19l).

d. Summary

Typically, the RVS phenomenon will occur when the TC is approaching or has moved poleward of the subtropical ridge axis. In this study, five of the seven cases of E-RVS involved a TC that was either already in the midlatitude synoptic pattern under the influence of the midlatitude westerlies or in a poleward flow region. Only two cases involved a TC that was in the S/TE synoptic pattern region south of the STR axis. In an environment of strong vertical wind shear, the forecaster needs to watch for excessive weakening or shallowing of the TC and the resultant lowering of the environmental steering layer for the TC. The dynamical model 500-mb fields will typically have a displacement of the TC circulation (usually a trough) several degrees down-shear of the low-level center. At the surface, the forecaster may note an increase in the minimum sea-level pressure in the model TC. The dynamical model tracks will have either a fast or slow along-track bias dependent upon the nature of the response (insufficient or excessive). However, a cross-track bias in not normally present. The

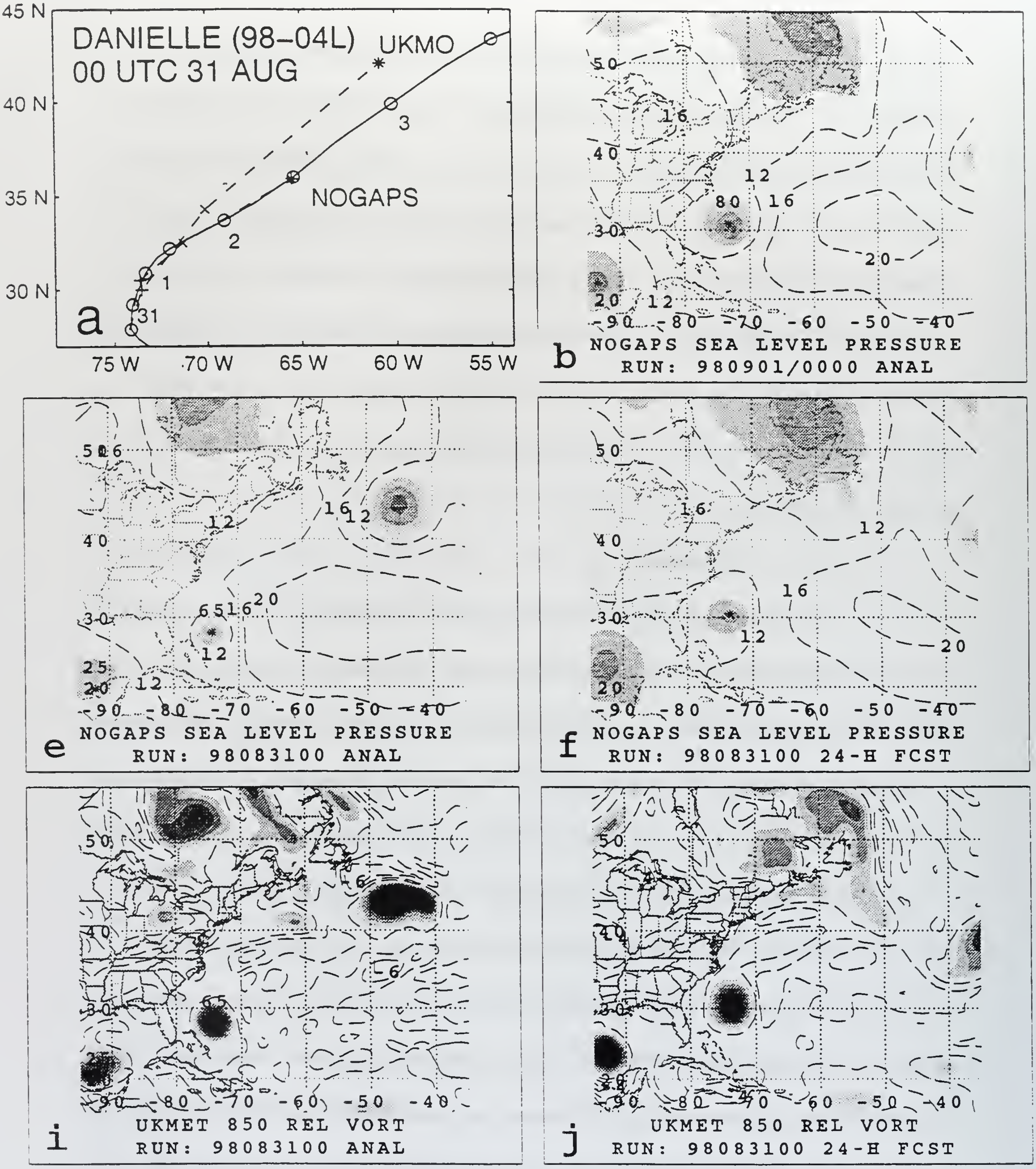

Figure 20. As in Fig. 19, except for NOGAPS sea-level pressure analyses and forecasts and UKMO 850-mb relative vorticity for Danielle initiated at 0000 UTC 31 August 1998.

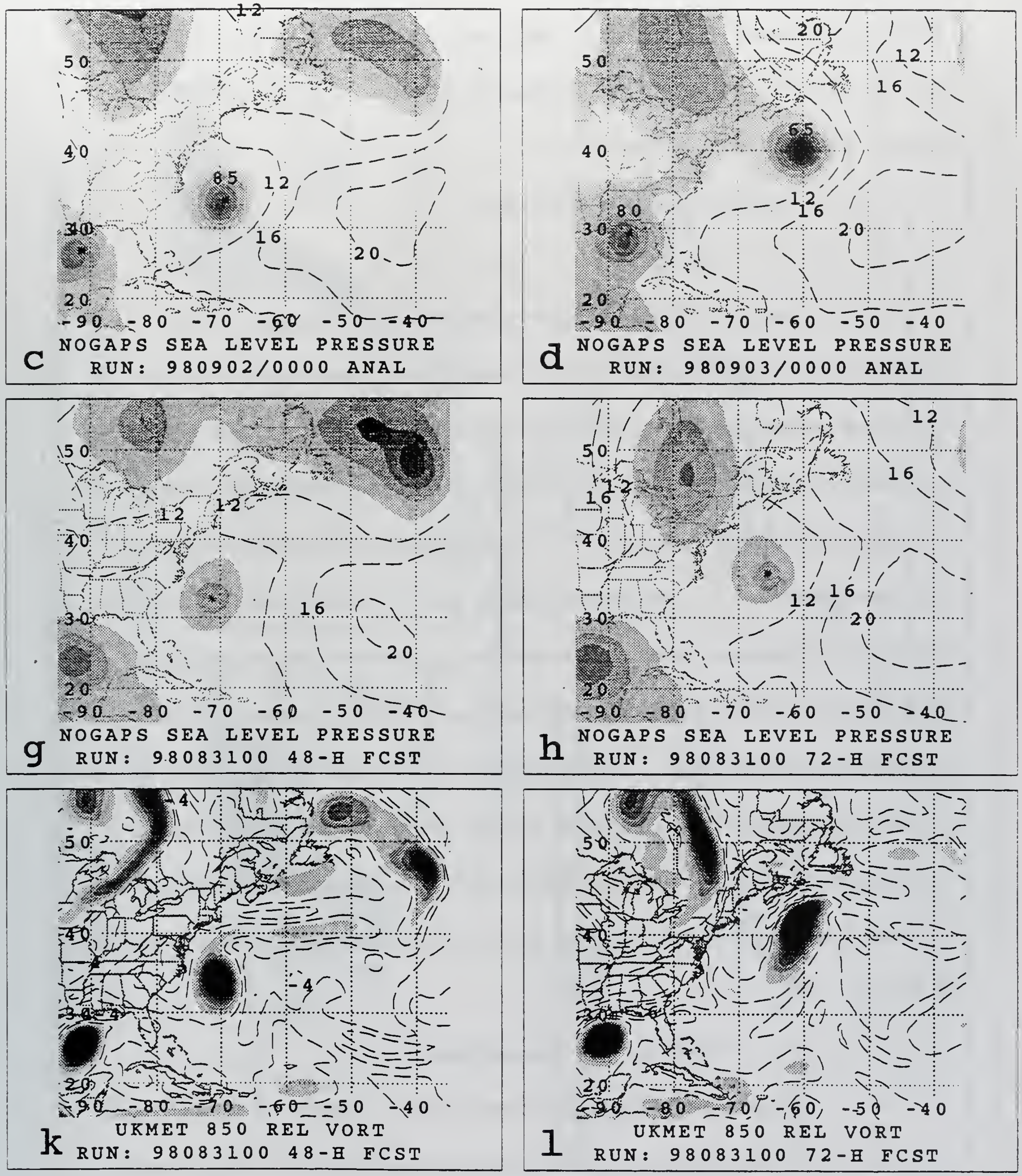

Figure 20. (continued)

BAM steering layer model tracks with large along-track differences in 72-h positions may provide an indication of RVS. The accuracy of the steering layer models will depend upon the steering layer of the TC.

2. Baroclinic Cyclone Interaction

a. Description

Carr and Elsberry (1999) describe erroneous Baroclinic Cyclone Interaction (BCI) to be occurring when the extratropical transition of a decaying TC is either over- or under-predicted such that a significant TC track error results (Fig. 21). Extratropical transition may occur when the TC is south of a midlatitude trough and to the west of a subtropical ridge cell. The TC will normally be in a Poleward Flow (PF) synoptic region of a S, P, or M synoptic pattern. The TC is drawn toward the region of midlatitude cyclogenesis, and may enhance the cyclogenesis region by amplifying the upper-level trough and by enhancing the warm- and cold-advection pattern in the favorable cyclogenesis regions. Excessive BCI occurs when the TC interaction with the region of cyclogenesis occurs too fast or falsely in the model, and this will result in a forecast track that has poleward bias. Insufficient BCI is classified if the interaction is too slow or does not occur in the model, and then the forecast track will have a slow bias (Fig. 21d).

b. Frequency and Characteristics

In the 1997-1998 sample of the NOGAPS, UKMO, and ECMWF track forecasts, 10 forecasts (based on model initialization time) involving three hurricanes were identified when BCI occurred sometime during the model integration (Table 8). Of these 10 forecasts of BCI, six were excessive in nature. The UKMO model was degraded

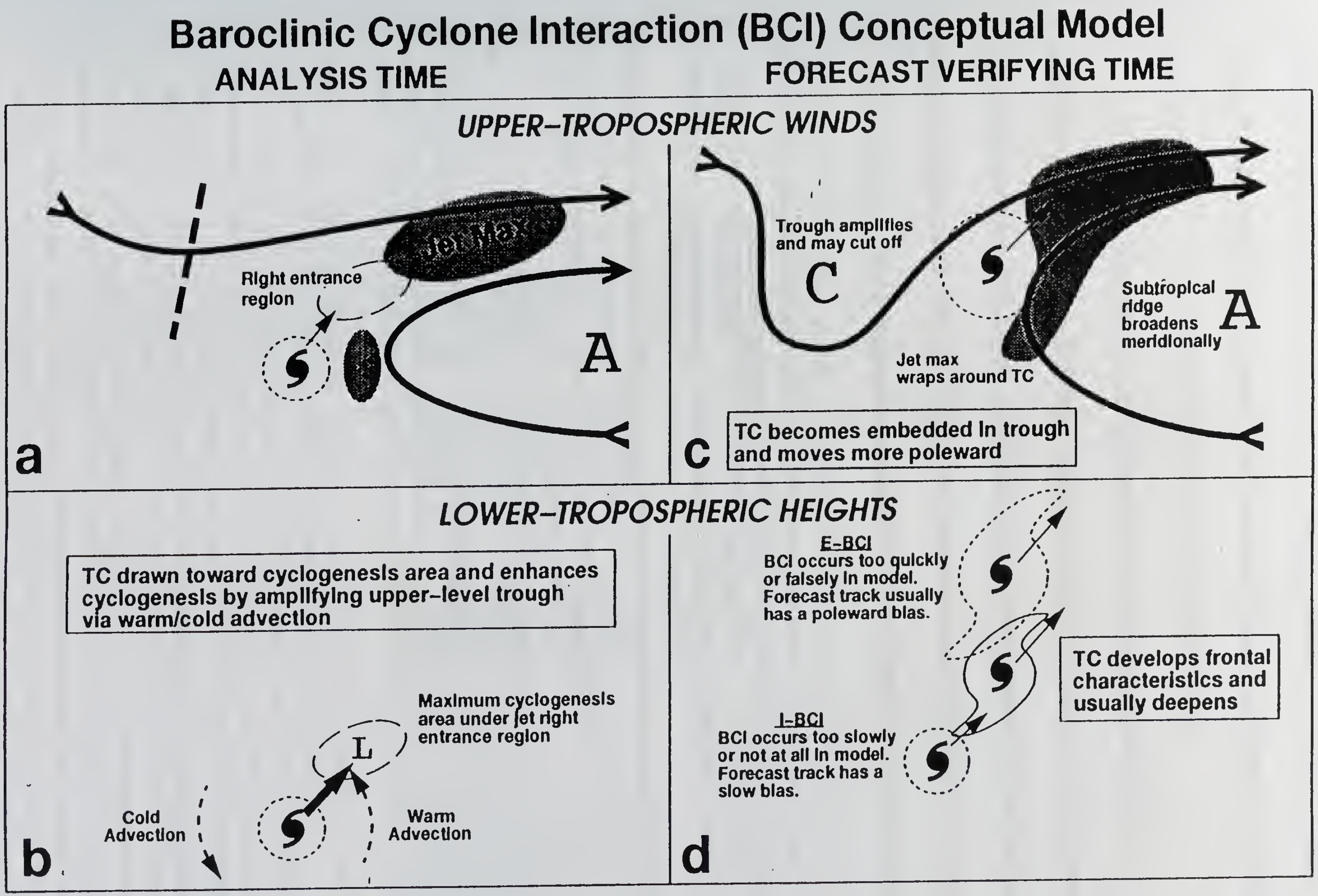

Figure 21. Schematics of two stages of Baroclinic Cyclone Interaction with a recurving TC that is potentially undergoing extratropical transition. Because the TC circulation has not been included, the blending of the environment flow (heavy streamlines) with the TC (dotted circle) in panel c would wrap around the TC. Modifications in the lower tropospheric thermal structure (panels b and d) lead to changes in the environmental steering of the TC (panel c). Excessive BCI usually results in a more poleward track bias and insufficient BCI results in a slow track bias (panel d) [from Carr and Elsberry (1999)].

most frequently by BCI. In addition, the BCI error mechanism only occurred in the second half of the hurricane season when baroclinic development is more likely.

c. *Case Study of Hurricane Nicole (98-14L)*

The NOGAPS forecast for Hurricane Nicole (98-14L) provides an example in which two model forecasts exhibit opposite BCI errors. For this late-season hurricane, the NOGAPS track forecasts initiated at 1200 UTC 27 November 1998 and 0000 UTC 28 November 1998 were affected by I-BCI (Table 8). In contrast, the UKMO track forecast initiated at 1200 UTC 27 November 1998 was affected by E-BCI.

Table 8. Cases of erroneous Baroclinic Interaction (BCI) in the North Atlantic during the 1997 and 1998 hurricane seasons. See Table 5 for explanatory footnotes.

TC No	Starting times of Affected model runs[1]	Initial synoptic environment of affected TC	Character of baroclinic interaction	Indications of contributing error mechanisms	Models Affected[5]
97-06L	Sep 09/00	P/PF	Insufficient		U
97-06L	Sep 12/00 → 12/12	M/MW	Excessive		U
97-06L	Sep 12/12	M/MW	Excessive		E
98-12L	Oct 06/12	S/PF	Insufficient	I-TCS	E
98-12L	Oct 06/12	S/PF	Excessive	E-MCG	U
98-14L	Nov 27/12 → 28/00	M/ME	Insufficient	E-RVS	N
98-14L	Nov 27/12	M/ME	Excessive		U
98-14L	Nov 28/12	M/PF	Excessive		U

At 1200 UTC 27 November 1998 Nicole is near 25.4°N, 41.7°W and is translating toward 277° at 12 kt (Fig. 22a). Nicole is in the M/ME pattern/region and is transitioning into the M/PF pattern/region during the forecast integration. During this period, Nicole intensifies from 30 kt to 65 kt. The NOGAPS forecast track (Fig. 22a) has a clockwise rotation with sharp recurvature occurring at 24 h. After the recurvature, the NOGAPS forecasts an eastward motion so that 72-h FTE of 264 n mi is primarily along-

track since the 72-h position is at the 48-h verifying best-track position. By comparison, the UKMO 72-h FTE of 544 n mi arises because the forecast position is well ahead of the best-track.

A comparison/verification of the NOGAPS and UKMO 500-mb wind fields from the integration initiated at 1200 UTC 27 November are given in panels b-l of Fig. 22 to provide a context for the period of I-BCI. At the initial time (Fig. 22e), Nicole is influenced by weak environmental steering as evidenced by the lack of an isotach maxima near the TC. A high-amplitude mid-latitude trough is located over the east coast of the U.S. and Canada. A ridge to the north of Nicole is also moving eastward and will merge with a ridge to the northeast. At 1200 UTC 28 November (Fig. 22b), a high-amplitude trough has become negatively-tilted and has propagated off the east coast of the U.S. to the northwest of Nicole. An isotach maximum is now northeast of Nicole, which is an indication of a transition to the M/PF pattern/region.

The NOGAPS 24-h forecast (Fig. 22f) does not have an isotach maximum to the northeast of Nicole and is slow to recurve the TC. However, the NOGAPS 24-h forecast does have a fairly good prediction of the amplitude and merging/reorientation of the anticyclone to the northeast of Nicole. The UKMO 24-h 500 mb forecast (Fig. 22j) is very similar to the NOGAPS forecast (Fig. 22f), yet only has a 24-h FTE of 19 n mi. At 48 h (Fig. 22g), the NOGAPS forecast has a cut-off low in the base of the trough to the northeast of Puerto Rico, and a ridge to the south of the TC, such that the isotach maximum is to the south. Nicole is now predicted to be in a region of more poleward steering vice weak steering and the NOGAPS forecasts a sharp 90° turn to the north (Fig. 22a). The UKMO 48-h forecast (Fig. 22k) is fairly consistent with the NOGAPS analysis

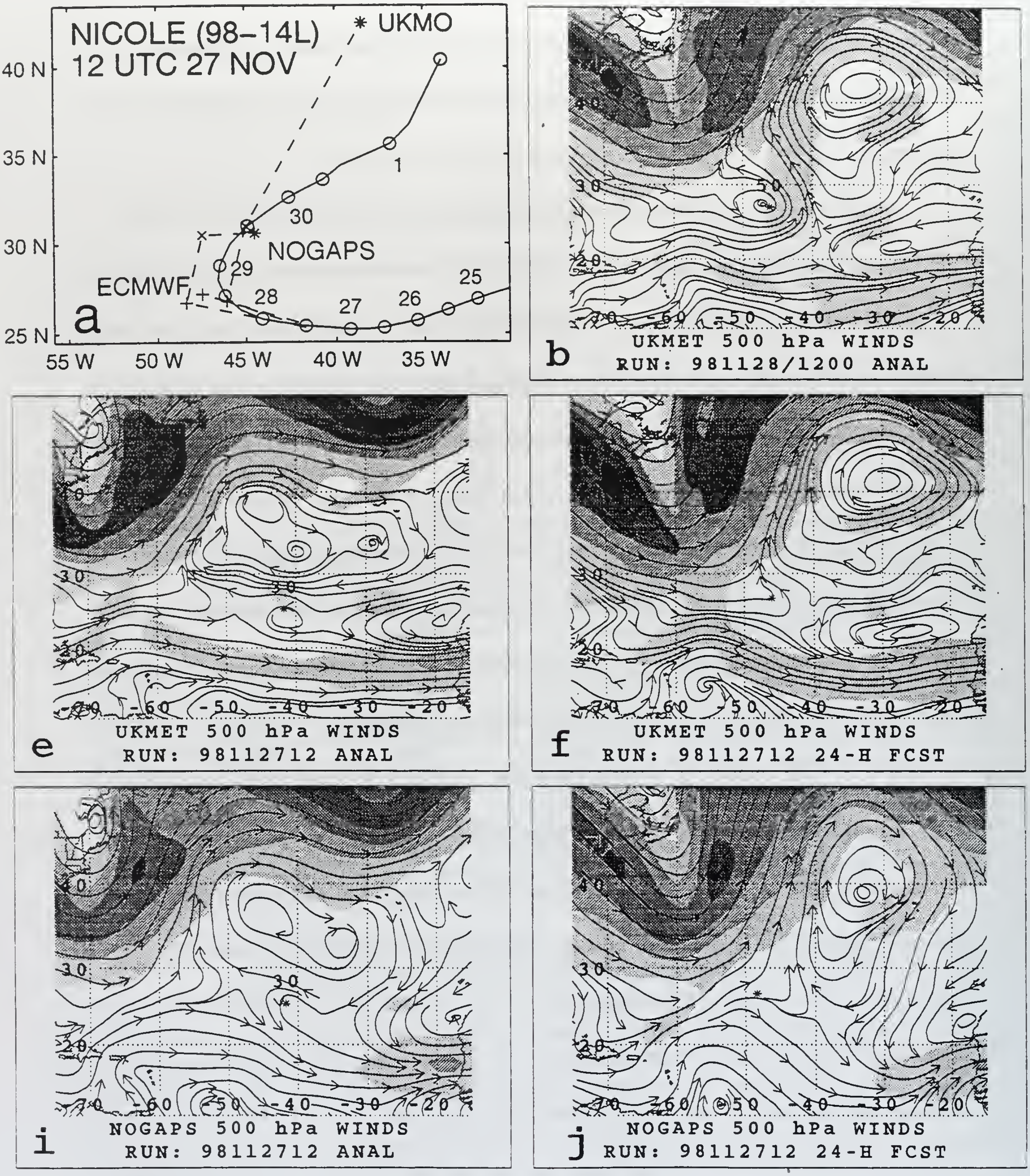

Figure 22. As in Fig. 8, except for NOGAPS and UKMO 500-mb wind forecasts for Nicole initiated at 1200 UTC 27 November 1998.

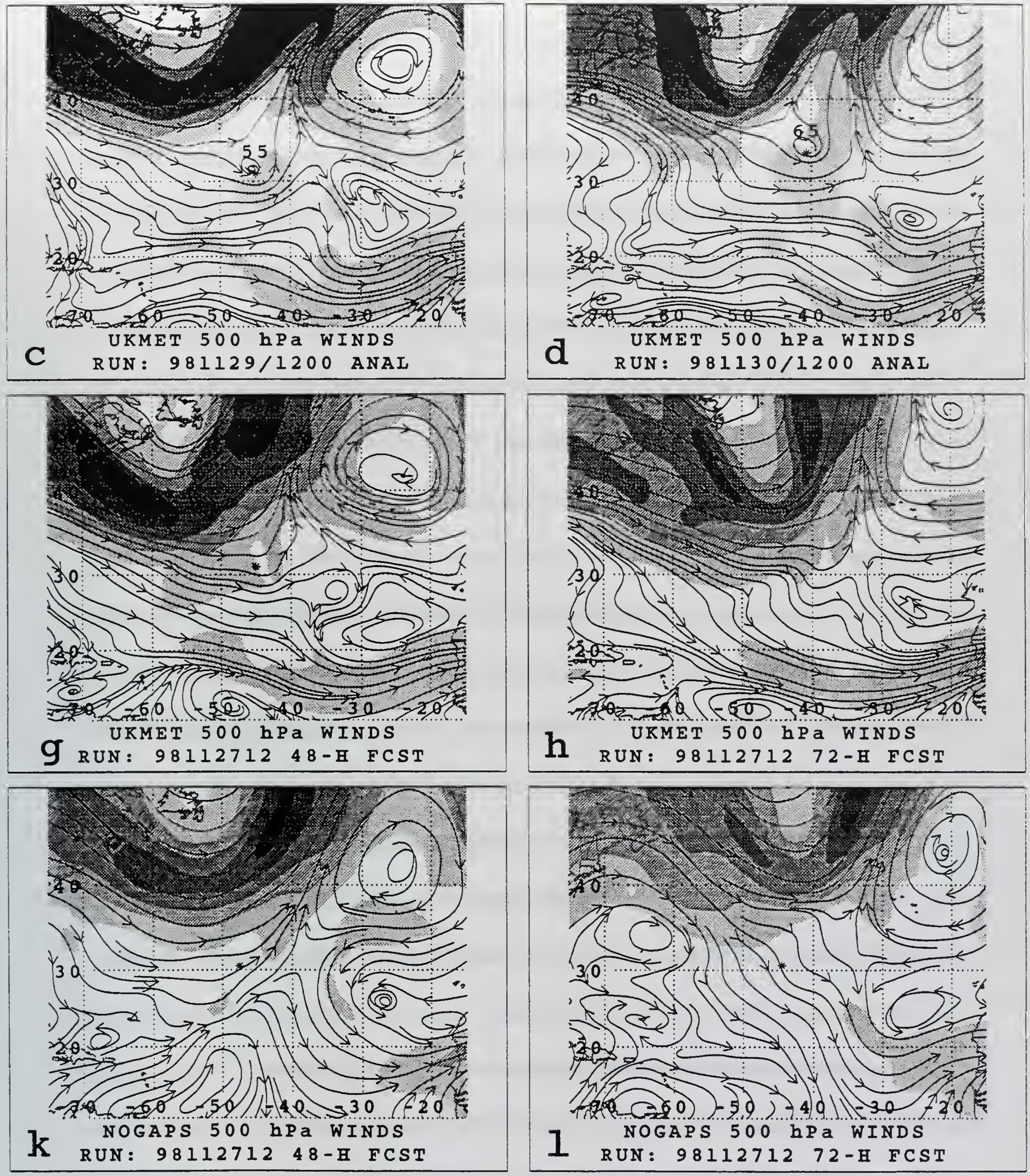

Figure 22. (continued)

(Fig. 22c). The only difference in the 500-mb fields is an isotach maximum to the west of Nicole in the UKMO forecasts, and yet the 48-h FTE is only 5 n mi. The NOGAPS 72-h forecast (Fig. 22h) has Nicole behind the midlatitude trough that is now moving to the northeast and thus keeps Nicole south of the prevailing westerlies. Overall, the NOGAPS forecast is too fast in moving the long-wave features from the mid-United States and through the central North Atlantic, and thus leaves the TC trailing behind. Although the UKMO 72-h forecast (Fig. 22l) is fairly consistent with the NOGAPS analysis (Fig. 22d), it has a weaker trough near 33°N, 38°W. However, the 72-h FTE is 544 n mi, which indicates the model TC is much farther to the northeast of the midlatitude trough.

A comparison/verification of the UKMO 850-mb relative vorticity and NOGAPS sea-level pressure fields are given in Fig. 23. Evidence for E-BCI in the UKMO model is best depicted in the 850-mb relative vorticity fields. The UKMO 24-h forecast of the low-level vorticity (Fig. 23f) associated with the midlatitude pattern to the northwest of Nicole described above has an elongated north-south orientation. At 48 h (Fig. 23g), the UKMO forecast has joined the vorticity center associated with the TC with that of the northern circulation. By contrast, the verifying UKMO 48-h analysis (Fig. 23c) has a more circular relative vorticity pattern at the TC location that is well separated from the northern circulation system, which has a vorticity signature that is much weaker than in the 48-h forecast (Fig. 23g). In the UKMO 72-h forecast (Fig. 23h), the vorticity signature of the midlatitude system is considerably stronger than in the verifying analysis (Fig. 23d). The objectively (vortex tracker) determined 72-h TC position is at the southern end of the midlatitude vorticity maximum, which suggests that the TC is

embedded in the midlatitude cyclone. However, notice that a lobe of high vorticity extends southward that nearly forms a closed maximum and that is located just to the north of the TC location in the 48-h UKMO forecast. This feature supports two possible interpretations. First, the vorticity extension may be just an expression of the intense cold front that would be expected to develop in the wake of a TC undergoing vigorous BCI. Second, the vorticity extension may actually be the remnants of the TC in the model, which is an interpretation that is supported by the similarity of the TC position in the verifying analysis (Fig. 23d). However, this correspondence could be purely coincidental. If the second interpretation is correct, then the highly erroneous UKMO track forecast for Nicole is actually a manifestation of the tracking algorithm erroneously jumping from the rapidly weakening TC vorticity maximum to the vicinity of the rapidly strengthening midlatitude cyclone vorticity maximum. The fact that the objective 72-h position is not precisely centered on the midlatitude vorticity maximum suggests that the second interpretation may be discounted in favor of the first. Regardless of which interpretation is correct, this case emphasizes the importance of evaluating and interpreting each dynamical model TC track forecast in the context of the synoptic situation depicted in the accompanying forecast fields, which must be available to the forecaster.

The opposing BCI errors mechanisms discussed above shows an example of the slow track bias of I-BCI (the NOGAPS forecast) and a fast track bias of E-BCI (the UKMO forecast). The forecaster must be aware of the variability of the BCI phenomenon and the rapidity in which the model can be affected by BCI.

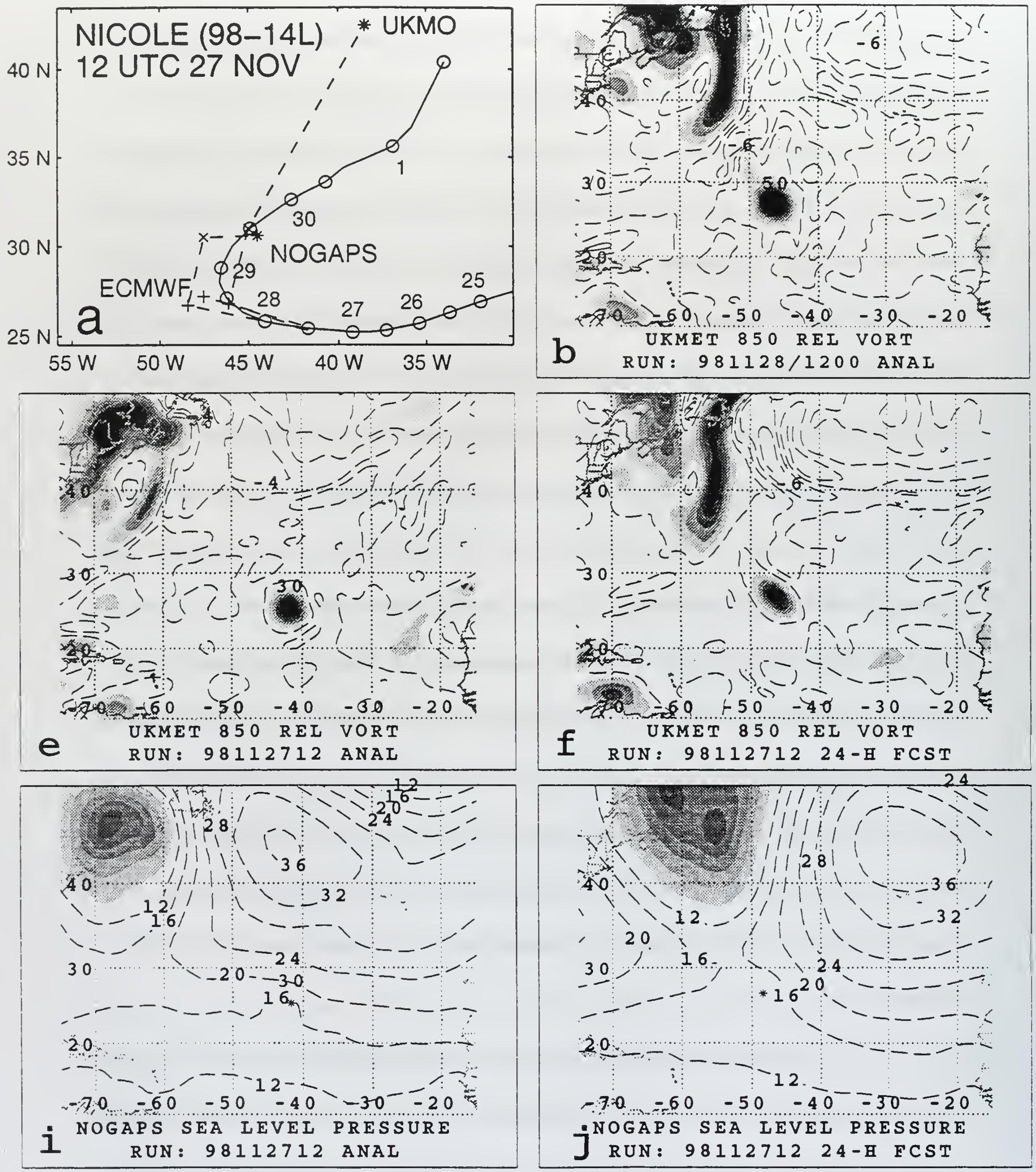

Figure 23. As in Fig. 22, except for UKMO 850-mb relative vorticity analyses and forecasts and NOGAPS sea-level pressure for Nicole initiated at 1200 UTC 27 November 1998.

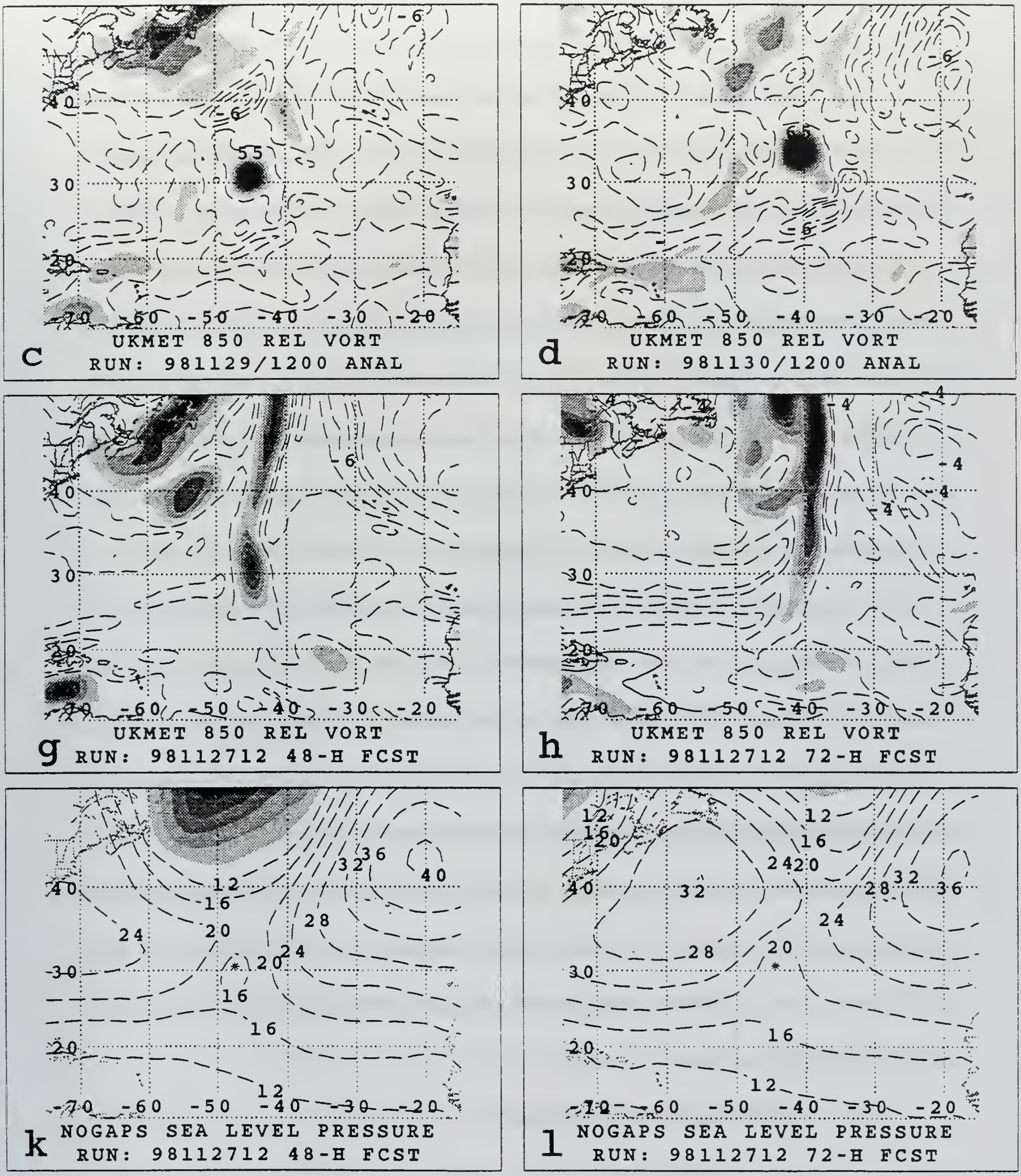

Figure 23. (continued)

d. Summary

While the above case study is not identical to the BCI of Typhoon Peter in the western North Pacific study of Carr and Elsberry (1999), it provides the forecaster some insight into the variations of the characteristics of BCI. The forecaster needs to be aware of the subtleties involved in recognizing BCI and the potential for other error mechanisms that may be occurring simultaneously, such as RVS and MCG (see Carr and Elsberry 1999). Indications of E-BCI in the 500-mb streamline fields include an over-development and displacement of a mid-tropospheric midlatitude cyclone toward the TC. The TC may then become embedded within the southerly flow ahead of the mid-tropospheric feature. At the surface, the forecaster must focus on the possibility of excessive deepening of the minimum pressure and horizontal growth in the size, or possibly an elongation and even dissipation of the TC. The dynamical model track bias may vary from slow to fast depending upon the predicted interaction between the TC and midlatitude feature. Indications of I-BCI are typically the opposite of E-BCI such that an under-development of the mid-tropospheric midlatitude circulation and smaller displacement toward the TC may occur. In addition, the TC may not become embedded in the southerly flow ahead of the midlatitude circulation, as in the NOGAPS case study of TC Nicole described above. Thus, the numerical model track forecast will normally have a slow along-track bias.

3. Midlatitude System Evolutions

a. Description

The basic idea of Midlatitude System Evolutions (MSE) as presented by Carr and Elsberry (1999) is one of changes to the TC steering flow due to midlatitude

circulation changes that essentially occur independently of the TC. The conceptual models for the four kinds of MSE are illustrated in Fig. 24. The key feature for Midlatitude CycloGenesis (MCG) is the development of a midlatitude trough or cyclone that alters the speed and/or direction of the environmental steering of the TC. If the TC is originally equatorward of the subtropical ridge axis and on a westward track, a developing midlatitude trough may create a "break" in the ridge and allow the TC to change to a poleward track. Conversely, a TC that is moving northwestward toward an existing break in the ridge, the track may be altered by a developing midlatitude ridge/anticyclone to the north that will change the steering flow of the TC to a more westward direction. With both scenarios of MCG or Midlatitude AntiCycloGeneisis (MAG), associated speed changes may accompany the directional changes.

b. Frequency and Characteristics

In the 1997-1998 sample of the NOGAPS, UKMO, and ECMWF track forecasts, 10 forecasts (based on model initialization time) involving eight hurricanes were identified when MSE occurred sometime during the model integration (Table 9). Six of the eight cases involved excessive MCG. Two of the eight cases were NOGAPS track forecasts degraded by excessive MAG.

c. Case Study of Hurricane Alex (98-01L)

For this TC, the ECMWF track forecasts initiated at 1200 UTC 27 July 1998 and the next two forecasts at 1200 UTC 28 July and 1200 UTC 29 July were affected by E-MCG (Table 3). At 1200 UTC 27 July, the TC is near 11.4°N, 25.5°W and is translating toward 287° at 18 kt (Fig. 25a) in the S/TE pattern region. The ECMWF 27 July forecast track (Fig. 25a) has an initial leftward (equatorward) bias and turns to the

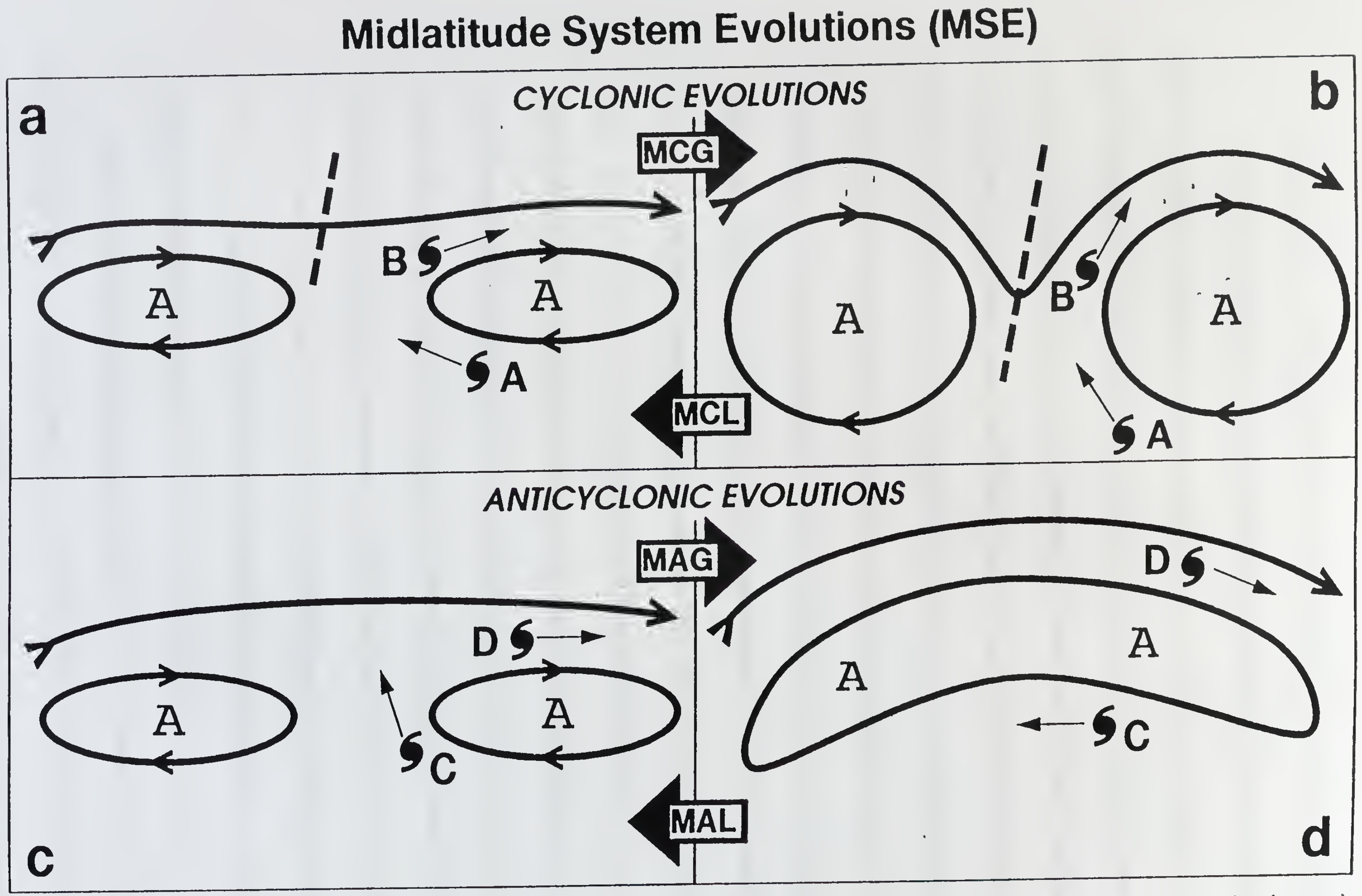

Figure 24. Schematics of the Midlatitude System Evolutions (MSE) that may lead to large TC track errors. The deepening of the midlatitude trough from panel a to panel b depicts Midlatitude CycloGenesis (MCG) and the reverse order (panel b to panel a) implies Midlatitude CycloLysis (MCL). Similarly, the midlatitude anticyclone change poleward of the TC from panel c to panel d depicts Midlatitude AnticycloGenesis (MAG) and the reverse order (panel d to panel c) implies Midlatitude AnticycloLysis (MAL) [from Carr and Elsberry (1999)].

Table 9. Cases of erroneous Midlatitude System Evolutions (MSE) in the North Atlantic during the 1997 and 1998 hurricane seasons. See Table 4 for meaning of acronyms in column 4. See Table 5 for explanatory footnotes.

TC No	Starting times of affected model runs[1]	Initial synoptic Environment Of affected TC	Type of erroneous Midlatitude System Evolution (MSE)	Models affected[5]
97-01L	Jul 01/00	M/MW	Excessive-MCG	U
97-01L	Jul 17/12	P/EW	Excessive-MAG	N
97-06L	Sep 05/12	S/TE	Insufficient-MCG	U
98-01L	Jul 27/12 → Jul 29/12	S/TE	Excessive–MCG	E
98-02L	Aug 27/12	M/PF	Excessive–MCG	E
98-07L	Sep 26/00	S/TE	Excessive–MAG	N
98-10L	Sep 27/12	S/PF	Excessive-MCG	E
98-12L	Oct 06/00	S/TE → S/PF	Excessive-MCG	U

northwest after 48 h so that the 72-h position is essentially on the track of the TC, but with a slow bias (72-h FTE of 396 n mi). Since the ECMWF model does not include synthetic TC observations during the model initialization, this may explain the initial position being well equatorward of the best-track position.

A comparison/verification of the ECMWF 500-mb wind fields and associated UKMO forecasts and analyses from integrations initiated at 1200 UTC 27 July 1998 is given in Fig. 25 to provide a context for the period of E-MCG. The feature of interest in the analysis and model forecast fields is the presence of an upper-level closed low northeast of the TC centered near 27°N, 22°W (Fig. 25i). At 1200 UTC 28 July (Fig. 25b), the TC is under the influence of a west-northwestward environmental steering flow with an isotach maximum in the northern quadrant. The closed upper-level low is still well to the northeast of the TC at this time. By 1200 UTC 29 July (Fig. 25c), weak troughing has extended southwestward to the north of the TC. However, the TC remains under the steering influence of the STR. By 72 h (Fig. 25d), the TC is clearly well

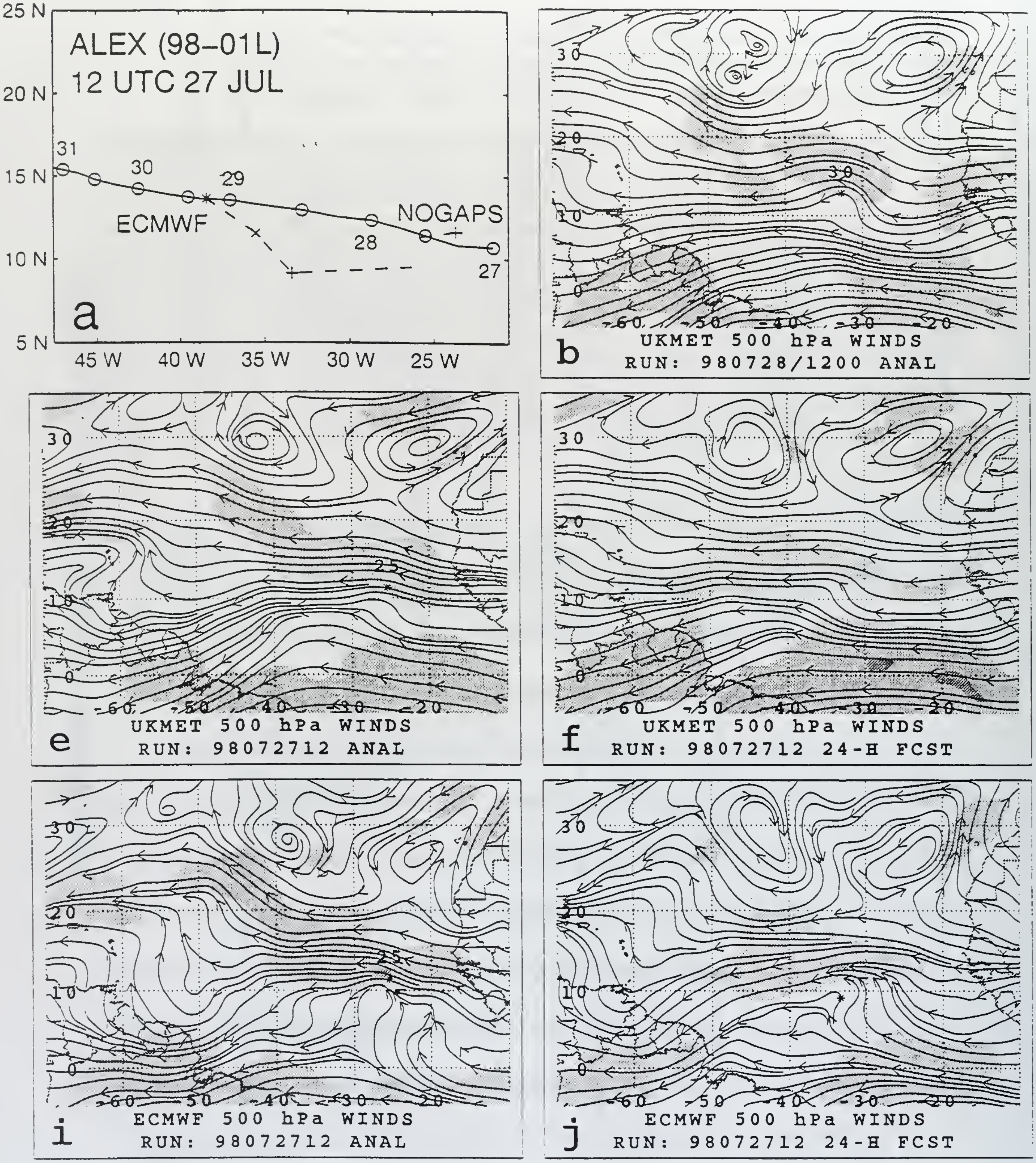

Figure 25. As in Fig. 8, except for UKMO and ECMWF 500-mb wind field forecasts for Alex initiated at 1200 UTC 29 July 1998.

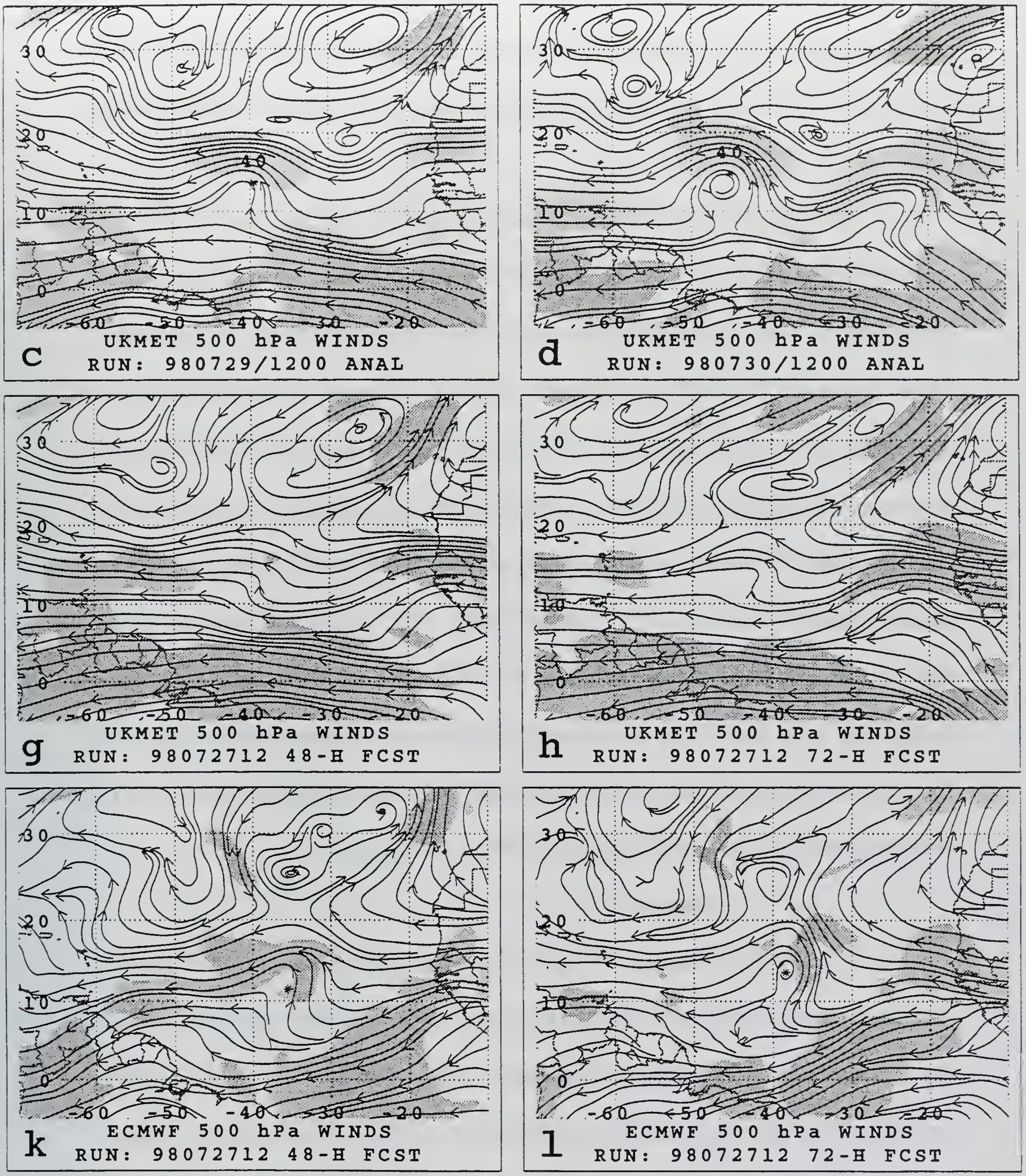

Figure 25. (continued)

defined as a closed mid-tropospheric circulation. The closed upper-level low to the northeast of the TC has weakened as ridging has occurred between the TC and the upper-level low.

In the 24-h ECMWF 500-mb forecast (Fig. 25j), the upper-level low to the northeast of the TC is predicted to be farther to the south than in the verifying UKMO analysis (Fig. 25b). By 48 h (Fig. 25k), the ECMWF forecast has split off a secondary closed low near 25°N, 35°W to the north of the TC. A stronger peripheral anticyclone to the east of the TC is also predicted by the ECMWF model than in the UKMO model, or in the analysis (Fig. 25c). Notice the isotach maximum has started to wrap around the east side of the TC, which indicates a change in the environmental steering flow and a possible false transition to the P/PF pattern/region. The 72-h ECMWF forecast (Fig. 25l) has a distinct mid-tropospheric cyclone to the north of the TC and a larger peripheral anticyclone to the east. Since the isotach maximum is now along the eastern quadrant, the peripheral anticyclone has become the primary environmental steering, and the TC has completed the false transition into the P/PF pattern/region.

d. Summary

This case study of TC Alex provides a variation of the E-MCG error mechanism, and is intended to alert the forecaster to the possibility of E-MCG occurring due to a mid-tropospheric cyclone propagating to the southwest from an initial position northeast of the TC. In a more typical scenario, the E-MCG would occur as a trough propagates off the eastern United States and weakens the STR to the north of the TC. Indications in the dynamical model fields of the E-MCG phenomenon include the

development of a deeper midlatitude trough or cyclone than in nature. Similarly, the surface forecast will have a deeper low develop.

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IV. CONCLUSION

A. FINDINGS

The Systematic Approach was developed to bring about quantitative and qualitative improvements to official TC track forecasting. The purpose of this thesis has been to expand the research to the North Atlantic basin via a documentation of the second major component of the Systematic Approach, which is a Model Traits knowledge base that describes how dynamical hurricane forecast track guidance performs in the North Atlantic region. The hypothesis was that the dynamical models will have similar characteristics and that cases with large errors in Atlantic TC track forecasts may be explained with the same eight conceptual models developed for the western North Pacific, and with similar relative frequencies as in that basin.

This study has examined large (i.e., > 250 n mi at 72 h) Atlantic TC track errors made by the dynamical models during the 1997 and 1998 seasons. The percentages of 72-h forecasts with a 250 n mi or greater FTE for the NOGAPS, UKMO, and ECMWF models were 23%, 26%, and 19%, respectively. For a homogeneous sample of 39 track forecasts in which the NOGAPS, UKMO, and ECMWF models produced a 72-h forecast for the same initial integration time, the average 72-h FTEs were 178, 204, and 144 n mi, respectively. Based on a student t-test, the average ECMWF FTE was significantly smaller than that of UKMO (NOGAPS) at the 99% (at least 90%) confidence value.

For each forecast time at which any of the models had a FTE greater than 250 n mi, a subjective error mechanism analysis as in Carr and Elsberry (1999) was conducted of the forecast fields of all three dynamical models. The results of this analysis will be the basis for a preliminary NOGAPS, UKMO, and ECMWF Model Traits knowledge

base for the North Atlantic. An important result of this thesis is that only three error mechanisms (E-DCI, E-RMT, and E-RVS) account for nearly 66% (19 of 29) of the poor NOGAPS track forecasts, and only three error mechanisms (E-DCI, E-RMT, and E-BCI) account for 57% (18 of 32) of the poor UKMO track forecasts for the North Atlantic TCs during 1997 and 1998. Due to the small ECMWF track forecast sample, the predominant error mechanisms are not well established.

In general, these error mechanism occurrences support the hypothesis that the dynamical models would have similar characteristics in the North Atlantic as for the western North Pacific. A modification of Table 4 is provided in Table 10 to compare the error mechanism occurrences for the North Atlantic and of the western North Pacific TCs during 1997 and 1998. The error mechanisms in rows DCI through RTF of Table 10 relate to TC-Environment Transformations in the Meteorological knowledge base (Fig. 1, lower right), and in each case the TC circulation interacts significantly with the surrounding environment. The error sources for the NOGAPS model are very similar for the two basins, with the North Atlantic and western North Pacific forecasts being degraded by these mechanisms in 55% and 58% of the cases, respectively. The error mechanisms in rows RVS through MAC in Table 10 involve large-scale midlatitude processes to which the TC is a comparatively passive respondent. Again, the error sources for the NOGAPS model are similar in the two basins, with the North Atlantic and western North Pacific forecasts being degraded by these mechanisms accounting for 28% and 37% of all cases, respectively. The larger percentage of forecasts that are not discernible or explainable in the North Atlantic may be attributed to the 250 n mi track error threshold as the definition of a large FTE.

Table 10. Meanings and frequencies of the causes of large NOGAPS, UKMO, and ECMWF forecast track errors. The numbers are the percentage of forecasts degraded by the listed error mechanism. If two number are listed, the first (second) is the percentage of times the phenomenon occurred excessively (insufficiently) in the model and corresponds to the E (I) prefixes in Tables 1, 2, and 3. Degraded track forecasts for the North Atlantic and western North Pacific are defined as > 250 n mi and > 300 n mi, respectively.

CAUSES OF DEGRADED TRACK FORECASTS DURING 1997-1998		NORTH ATLANTIC			WESTERN NORTH PACIFIC		
Phenomenon Name	Acronym	NOGAPS	UKMO	ECMWF	NOGAPS	UKMO	ECMWF
Direct Cyclone Interaction	DCI	28-0	25-0	0	38-0	38-0	18-0
Semi-Direct Cyclone Interaction	SCI						
SCI on Western TC	SCIW	0	0	8-0	2-0	2-0	6-0
SCI on Eastern TC	SCIE	0	0	0	0	0	0
Indirect Cyclone Interaction	ICI						
ICI on Eastern TC	ICIE	3-0	3-0	15-0	0	0	0
ICI on Western TC	ICIW	0	0	0	0	0	0
Ridge Modification by TC	RMT	24-0	16-3	0	11-0	6-0	6-0
Reverse Trough Formation	RTF	0	3-0	0	7-0	7-0	12-0
Response to Vertical wind Shear	RVS	14-0	9-0	0	8-0	4-2	15-0
Baroclinic Cyclone Interaction	BCI	0-7	16-3	8-8	14-9	34-1	15-18
Midlatitude Systems Evolutions	MSE						
Midlatitude CycloGenesis	MCG	0	6-0	38-0	0	1-0	0
Midlatitude CycloLysis	MCL	0	0	0	0-1	0	0
Midlatitude Anticyclogenesis	MAG	7-0	0	0	4-0	1-4	3
Midlatitude AntiCyclosis	MAC	0	0	0	0-1	0	0
Tropical Cyclone Initial Size	TCS	0-7	0	23-0	3-0	0	0
Not discernible or explainable		10	16	0	1	2	6

B. FUTURE RESEARCH

This thesis expanded the research in the North Atlantic via a documentation of the second major component of the Systematic Approach, which is a Model Traits knowledge base. Only the NOGAPS, UKMO, and ECMWF dynamical models could be evaluated at this time. The NLMOC forecaster has additional dynamical and objective guidance available, especially the GFDL model that has provided excellent track guidance since it became operational in 1995. An error mechanism analysis should be conducted on these additional models to expand the Model Traits knowledge base. In addition, the sample size for this study is small compared to the western North Pacific research of Carr and Elsberry (1999). The addition of cases from previous years and

from 1999 would create a more thorough Model Traits knowledge base for the North Atlantic.

REFERENCES

Boothe, M. A., R. L. Elsberry, and L. E. Carr III, 1999: Atlantic Application of the Systematic Approach to Tropical Cyclone Track Forecasting. Part I. Environmental structure characteristics. Tech. Rep. NPS-MR-99-003, Naval Postgraduate School, Monterey, CA 93943-5114, in press.

Carr, L. E., III, and R. L. Elsberry, 1994: Systematic and Integrated Approach to Tropical Cyclone Track Forecasting. Part I. Approach overview and description of meteorological basis. Tech. Rep. NPS-MR-94-002, Naval Postgraduate School, Monterey, CA 93943-5114, 273 pp.

Carr, L. E., III, and R. L. Elsberry, 1999: Systematic and Integrated Approach to Tropical Cyclone Track Forecasting. Part III. Traits knowledge base for JTWC track forecast models in the western North Pacific. Tech. Rep. NPS-MR-99-002, Naval Postgraduate School, Monterey, CA 93943-5114, 227 pp.

Commander, Naval Meteorology and Oceanography Command, cited 2000: Hurricane Havens Handbook for the North Atlantic Ocean. [Available on-line from http://www.cnmoc.navy.mil/nmosw/tr8203nc/0start.htm]

Commander, Naval Meteorology and Oceanography Command, cited 2000: Strategic Plan. [Available on-line from http://www.cnmoc.navy.mil]

Kent, C. S. T., 1995: Systematic and Integrated Approach to Tropical Cyclone Track Forecasting in the North Atlantic. M. S. Thesis, Naval Postgraduate School, Monterey, CA 93943, 76 pp.

Swaykos, J. W., and T. E. Bosse, 2000: Navy Tropical Cyclone Prediction Developments and their Impacts on Fleet Operations. 54th Interdepartmental Hurricane Conference, Houston, TX, 14-19 February.

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